ERRATA.

PAGE III, foot of page:

1 cubic metre $CO+\frac{1}{2}$ cubic metre $O=2$ cubic metres CO_2

should read

1 cubic metre $CO+\frac{1}{2}$ cubic metre $O=1$ cubic metre CO_2

PAGE 227, foot of page;

The paragraph marked (2) refers to table 93.

THE

MANUFACTURE AND PROPERTIES

OF

STRUCTURAL STEEL.

BY

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To

All Those, Famous or Obscure,

Who, by the Furnace, in the Shop, or at the Desk,

Are Joining Hand and Brain to Solve the

Problems of

The Metallurgic Art,

This Volume is Fraternally Dedicated.

INTRODUCTION.

Within the last decade America has made marvelous developments in her iron industry, until now she leads the world in the quantity of her products, and bows to none in their quality. The relative position of the great industrial nations will be evident from a glance at Table 1.

TABLE 1.

Average Yearly Production of Pig-Iron and Steel by the Leading Four Nations.

Figures are in metric tons and are taken from Vol. IV of *The Mineral Industry.*

Period.	United States.	Great Britain.	Germany.	France.
Pig-Iron.	Tons per year.	Tons per year.	Tons per year.	Tons per year.
1880-1884 inclusive	4,328,796	8,260,298	3,232,838	1,918,335
1885-1889 "	6,175,197	7,752,625	4,020,345	1,626,439
1890-1895 "	8,444,713	7,495,068	5,093,547	2,000,586
Steel.	Ton. per year.	Tons per year.	Tons per year.	Tons per year.
1880-1884 inclusive	1,586,421	1,861,713	978,683	458,855
1885-1889 "	2,822,435	3,000,092	1,626,698	498,004
1890-1894 "	4,374,484	3,168,979	2,514,874	645,958

This wonderful progress has not been the unearned harvest of bounteous nature, for it has been accomplished in defiance of mighty obstacles in the enormous distances through which the raw materials must be carried, and, although the achievement may be a just source of national pride, it involves inevitable expenses and disadvantages which may be lessened by energy, but which can never be swept away.

The progress in quantity of product has been accompanied by a corresponding improvement in the quality, due in great measure to the requirements of the engineering profession. The present generation has discarded the use of wrought-iron in general construction, and it is now used only by those engineers who are a legacy of an ancient régime and who refuse to

keep pace with the advances in knowledge. This is essentially the age of steel, and, while a few of the following pages are devoted to the making of wrought-iron, their end and aim is to describe in concise form, for the use of constructive engineers, the manufacture and the nature of the newer material.

As having an important bearing upon the question, it has been thought best to devote much space to those processes by which most of the iron products of commerce are made. These chapters on purely metallurgical subjects can not pretend to be complete, but they aim to present the main features, and to show that the makers of steel are doing what they can to discover the laws that govern their art. In other chapters are recorded some investigations upon the physical qualities of steel. It would be too much to expect that any such limited series of tests could forever settle all disputed points, but it is hoped that the work is on the right road in the effort to have all experiments conducted under constant conditions, in order that the variable determinants shall be reduced to the smallest possible number.

In many places I have cited the opinions and experiments of leading metallurgists, especial prominence being given to the researches of H. M. Howe and R. A. Hadfield. In all instances, reference is made to the source of information. This rule is not followed in the case of my own writings, so that it may be well to state that the chapters relating to open-hearth practice and to fuel have been condensed from certain papers of mine, which may be consulted by those desiring fuller information in the *Transactions of the American Institute of Mining Engineers*, Vol. XIX, pp. 128 to 187, Vol. XX, pp. 227 to 232, and Vol. XXII, pp. 345 to 511, and 679 to 696. Portions of chapters XVI, XVII, and XVIII, have very recently appeared in the *Transactions of the American Society of Civil Engineers*, April, 1895, but in this case the present book is an amplification rather than a condensation, of the paper.

No attempt is made to prove any novel metallurgical theory, nor is there any argument, in the chapters on structural steel, in favor of relieving manufacturers from furnishing the best material. On the contrary, the recommendations are in the line of greater stringency, since the true pride of the manu-

facturer should be the elevation of the standard above the reach of his less skilled competitors. The experiments and investigations, except where otherwise stated, have been conducted at the works of The Pennsylvania Steel Company at Steelton, Pa., and all the details of manufacture and treatment have been under my direct observation. The chemical work was done by Mr. Geo. P. Vanier, who rendered hearty coöperation, while acknowledgment is also due to Mr. H. B. Bent, of our testing department, for assistance in laborious compilations and computations.

H. H. CAMPBELL.

STEELTON, PENN., December, 1895.

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INDEX TO ABBREVIATIONS.

A. I. M. E.—American Institute of Mining Engineers.

Am. Soc. Civil Eng.—American Society of Civil Engineers.

A. S. Mech. Eng. or *Am. Soc. Mech. Eng.*—American Society of Mechanical Engineers.

Journal Frank. Inst.—Journal of the Franklin Institute.

Journal I. and S. I., or *I. and S. I. Journal.*—Journal of the Iron and Steel Institute of Great Britain.

Proc. Inst. Civil Eng.—Proceedings of the Institute of Civil Engineers (England).

Proc. English Inst. Mech. Eng.—Proceedings of the English Institute of Mechanical Engineers.

Trans. A. I. M. E.—Transactions of the American Institute of Mining Engineers.

Trans. A. S. Mech. Eng., or *Trans. Am. Soc. Mech. Eng.*—Transactions of the American Society of Mechanical Engineers.

Trans. Am. Soc. Civil Eng.—Transactions of the American Society of Civil Engineers.

C by comb.—carbon as determined gravimetrically.

C by color.—carbon as determined by the color method.

Graph.—graphite.

Tr.—trace.

Und. or *undet.*—undetermined.

MANUFACTURE

AND

PROPERTIES OF STRUCTURAL STEEL.

CHAPTER I.

THE ERRANCY OF SCIENTIFIC RECORDS.

SECTION 1.—*Examples of errors in metallurgical publications.*—We have all heard much of the higher criticism in connection with the historical writings of antiquity, but it will seem strange to many if I urge the application of this highest of all arts to the one field where exactness and clear reason are supposed to reign supreme. A scientific statement of a definite determination is usually assumed to be correct, save by a certain unimportant experimental error. Unfortunately, this child-like faith is too often misplaced, and the careful student builds his theories on the errors of ignorance and carelessness.

A notable instance of this may be found in our own special field of metallurgy. The foremost book on iron and steel in our language is the massive volume by H. M. Howe, entitled, "The Metallurgy of Steel." The author of this great work has carefully searched the records of the scientific societies of the world, and has given us all the available data to be found bearing upon the problems of steel manufacture. In the quest for general laws from laboriously constructed tables, and in the discussion of erudite matters of theory, he has

been guided by a keen acumen which has placed many of his generalizations above dispute. And yet, occasionally, in the compilation of some of the tables, there is a most unfortunate readiness to accept the most glaring absurdities.

An illustration of this may be found on page 18 of "The Metallurgy," in the table showing the effect of hardening upon various iron compounds. Test No. 11 is a Bessemer steel with .33 per cent. carbon, 51259 pounds ultimate strength after annealing, and 19 per cent. elongation. This is, indeed, a strange metal, and the internal evidence of error should have caused the record to be thrown out. The mistake is not in the types, for it is gravely recorded that the strength of the original bar was 37 per cent. higher, or 70225 pounds per square inch. Now, if the annealed bar gave 51259 pounds ultimate strength, and the natural bar 70225 pounds, it is evident that the piece must have been cold-rolled, or otherwise specially treated, and therefore entirely unfit for comparison with normal steel.

But if we suppose that the figure 51259 is an error, then the extraordinary character of the metal disappears; for, with .33 carbon, an ultimate of 70,000 pounds would not be abnormal, and 19 per cent. elongation would be quite in order, particularly as the length of the test-piece is not given. With this change, however, the figures relating to hardening become worthless.

The next line of the before mentioned table gives the tests on a steel of 82000 pounds ultimate strength. This is marked "homogeneous metal," and the carbon is given as .40 per cent., this figure being followed by a question mark. It is difficult to understand why the carbon determination is doubted, for the analysis and the tensile strength correspond quite well. But whatever may have been the practice in the days gone by, it is certain that the meaningless epithet of "homogeneous metal" is not and never was applicable to a steel of .40 carbon.

This absurdity of nomenclature is quite cast in the shade, however, by the astonishing classification, by the same experimenter, of metal showing over 100,000 pounds ultimate strength as "rivet steel." Mr. Howe has kindly put an interrogation mark after the figure showing 1.00 per cent.

carbon, but whether the question concerns the "cast steel" or the "Bessemer steel", or this remarkable "rivet steel," he omits to mention.

In the above illustration of the errancy of the printed page, I have selected Mr. Howe as my target, not because he is the most flagrant offender, but because he is the most eminent; because his book is used by us all as an authority, and its responsibility must be measured by its fame.

Sec. 2.—*Variations in the results of experiments due to the accumulation of petty errors.*—Errors like the foregoing arise from different causes. They may come from mixing of test-pieces in the shop, the testing-room, and the laboratory, or from miscalculations and mistakes in measuring and copying the figures. Instances of such blunders can be found in every establishment, and the only true remedy is the repetition of the entire work. Even when the utmost care has been exercised, the results must not be translated too literally, for there are variations which are due solely to the cumulative effect of petty determinative errors. Thus, I made the experiment of cutting six tests from the same bar and having them measured, pulled and calculated by the same man. The original piece was a rolled flat, 4 inches wide by 5-16 inch thick. This was cut lengthwise into two strips, 1¾ inches wide by 5-16 inch thick, and these strips were again cut into 18-inch lengths. Six of these, taken from alternate sides of the original bar throughout its length, were tested without treatment. The results are given in Table 2.

Whether the determinations of sulphur and phosphorus are absolutely correct is of no importance, for it is certain that the total amount of impurity is very small, and the probable variation in chemical composition in different parts of such a bar may be neglected. In regard to the physical condition, it should be said that the piece was made from a billet, which in turn had been rolled from a 2-ton ingot; the bar was therefore more uniform throughout than any two different bars would likely be; and yet we find a variation of 1400 pounds in ultimate strength; 3030 pounds in elastic limit; 9.5 per cent. in elongation; 3.20 per cent. in reduction of area, and 4.54 per cent. in elastic ratio.

Pourcel,* citing from one of my own papers, gives results differing but little more than this to prove the non-homogeneity of steel as produced by segregation; by a strange irony of fate, he takes the records which I had confidently published to show that our steel was homogeneous and uniform. Nothing will better indicate the effect of a preconceived thesis upon the reasoning faculty.

TABLE 2.

Variations in Physical Properties of Pieces of the Same Rolled Bar.

Size of bar, 1¾"x5-16". Composition, per cent., C (by combustion) .057, P .006, Mn .33, S .019.

No. of Piece.	Ultimate strength; pounds per square inch.	Elastic limit; lbs. per square inch.	Elongation in 8 in.; per cent.	Reduction of area; per cent.	Elastic ratio; per cent.
1	46730	33500	31.00	72.00	71.69
2	45560	32760	36.25	70.60	71.91
3	45950	34420	33.50	68.80	74.91
4	45710	32750	34.00	68.80	71.65
5	46960	35780	37.00	69.70	76.19
6	45680	33740	40.50	70.10	73.86
Average,	46 98	33825	35.37	70.00	73.37

SEC. 3.—*Errors in chemical methods.*—Aside from the disturbing factors in the shop and testing-room, there are great and important errors in the work of the chemical laboratories. This will seem a reckless statement to those not conversant with the limitations of chemical science. The average chemist is well grounded in the belief that his determination of carbon by combustion is absolutely beyond question, and if some other chemist disagrees with him, it is the misfortune of that analyst. Not only is he quite certain of this result, but he regards his color determinations as above all but captious criticism. Such is the position of many a steel-works chemist, and the metallurgical compiler must accept his records as inerrant. It seems pertinent, therefore, to recite the following:

* *Segregation and its Consequences in Ingots of Steel and Iron. Trans. A. I. M. E.*, Vol. XXII, p. 108.

In 1888 the chemical societies of the world arranged among themselves to investigate the methods of steel analysis. At one of the first meetings of the American committee it was found that the different ways of determining carbon did not give concordant results, and a special investigation was instituted to discover the causes of error. The result may be told by quoting the report of Prof. Langley,* one of the committee: "It is perhaps not too much to say that sufficient work has already been done to throw doubt on the accuracy of all recent determinations made with preliminary solution of the steel in double chloride of copper and ammonium."

This opinion has been reiterated in Vol. XX, p. 242, where it is stated that all commercial chlorides of copper and ammonium contain carbon, and that their use in steel analysis gives too high a carbon percentage.†

TABLE 3.

Variations in the Results obtained by Different National Committees on the Same Steel.

No. of Sample.	Nationality of Committee.	Composition, per cent.				
		C	Si	S	P	Mn
1	English,	1.414	.263	.006	.018	.259
	Swedish,	1.450	.257	.008	.022	.282
	American,	1.440	.270	.004	.016	.254
2	English,	.816	.191	.007	.014	.141
	Swedish,	.840	.185	.004	.015	.145
	American,	.800	.202	.004	.010	.124
3	English,	.476	.141	.008	.021	.145
	Swedish,	.500	.150	.006	.021	.170
	American,	.454	.152	.004	.015	.140
4	English,	.151	.008	.039	.078	.130
	Swedish,	.170	.015	.048	.102	.130
	American,	.180	.015	.038	.088	.098

Since these reports have been published, the committees have been at work, and in the *Journal of the American Chemical Society*, Vol. XV, No. 8, is given a partial report of progress, while in *The Chemical News*, Vol. LXVII, No. 1766, further results are published. Table 3 shows a condensation of the records thus far made public.

* *International Standards for the Analysis of Iron and Steel. Trans. A. I. M. E.*, Vol. XIX, p. 623.

† It should be said that a pure article is now in the market, and that all chemists do not agree that the use of this reagent has caused errors of vital importance.

It must be borne in mind that these analyses were conducted under the most favorable conditions which could possibly exist. The chemists were men of recognized and eminent ability, especially selected as worthy of their important task. Each fully understood that his reputation depended upon his report. He must agree with his co-workers or, if differing, must establish to the satisfaction of the world that his methods were right, or else that there was some disturbing factor previously unknown to the chemical world. He was not confined to any one determination, but could repeat as often as desired, and compare with the work of assistants until the record stood for his highest accuracy. Not content with assuming ordinary risks, many blank determinations could be carried through to make sure of the quality of the reagents; of the effect of varying moisture in the atmosphere; and the many minor conditions that influence solution, precipitation and absorption.

With all these abnormal refinements, the carbon determinations vary in one standard from .45 to .50 and in another from .15 to .18. The other elements also show variations, and it must not be forgotten that these results are not separate and extreme instances, but that each is the average of many results and of several chemists. A table of extremes of separate determinations would be most interesting reading. Even with the above records we are justified in doubting any chemical determination. Many records are published on the verbal statements of uneducated metallurgists, whose uncertain memory of facts not originally proven, is befogged by crochety prejudices. Some are taken from laboratory notebooks with too little care in the detection of clerical errors. Others are the results of methods which have been condemned by all chemists save the one using them, while still more have been obtained by methods which, though looked upon as correct at the time the analyses were made, have been found to be inadmissible. Few, very few, have been made by chemists whose work is being continually checked by the parallel results of other analysts of known excellence. Even were this last requirement met, it has been shown that scientific certainty would by no means be obtained.

From the foregoing remarks it may be seen that the com-

parison of miscellaneous records is perfectly useless and misleading. Even the results of two different well-conducted laboratories and works may not be trustingly placed together. This can be done if the two works in question exchange samples, and find that both obtain similar results from the same metals, but under no other circumstances is the comparison valid.

Sec. 4.—*Necessity of uniformity in chemical work.*—It may appear that these conclusions put in question the value of chemical work, but such is not the case. The one thing desired above all others in practical manufacture is consistency of results, and, having this quality, the absoluteness may be dispensed with. A striking example of this happened in my own experience. We discovered many years ago that we had been running with an error of .11 per cent. in all our low carbon determinations, and .13 in all the high steels. Thus steel of .09 carbon had been regularly determined as .20, and .50 carbon as .63. Customers ordered steel, found it right, or found it too hard or too soft, and ordered the next lot accordingly. Years had rolled by and every customer knew just what he wanted, and could learnedly discuss the special nature of .64 and of .76 carbon. The discovery of the error in the standards was a rude shock, and the change to the new order of things was the work of many months, and a diplomatic catering to prejudice, mixed with a very strong disinclination to an open acknowledgment that we had been altogether wrong.

In these later days it is customary to have the standards analyzed by several chemists, and to take an average between results, which always differ. It has also been found essential, whenever color comparisons are to be made, that a standard of nearly the same composition be dissolved at the same time and under the same conditions as the steel under treatment. This refinement was certainly not observed in many analyses of the past.

As before noted, the errancy of the records is not confined to the carbon, for sulphur is another offender. Three of the samples have only a trace at best, and hence a difference of 100 per cent. will not be discussed. But the results on the fourth sample, showing .038 by one average and .048 by an-

other, is a more important matter. When United States Government contracts specify that sulphur must be below .04, and when steel is rejected because it shows .042 by the analysis of a naval engineer, it is time that the standard methods should not give a variation such as these records show.

The differences in silicon are unimportant, and the same may be said of manganese, although these determinations do not shed lustre on chemical science.

It is in phosphorus that the most astonishing revelation appears. An error of 50 per cent. in steels of about .02 is bad enough, for contracts are made with that point as a limit, but the fourth sample is a catastrophe. In the structural world the limit .10 is looked upon as the maximum percentage admissible. Some few engineers, who desire a better class of material, specify that .08 shall be the maximum. Yet so great are the errors of the highest chemical research, that this sample (No. 4) is condemned by one committee as unfit for the most common work, while another approves it as of extra quality.

SEC. 5.—*Variations in the parallel determinations of practicing chemists.*—It may be a fall in dignity to leave these determinations of the picked chemists of the world and discuss the results of everyday work, but it is assuredly of vital importance to know how much reliance can be placed upon commercial records. At the Virginia Beach meeting of the A. I. M. E., in February, 1894, W. R. Webster recounted an investigation by Mr. Vauclain of the Baldwin Locomotive Works, wherein two pieces of boiler plate were each cut into five parts and sent to five different steel works for analysis. The greatest differences in the results were as follows:

Carbon	0.17 to 0.23 per cent.
Manganese	0.33 to 0.42 " "
Phosphorus	0.041 to 0.055 " "
Sulphur	0.019 to 0.043 " "

In commenting upon these figures, the opinion was expressed by Mr. Vauclain that the divergence was probably due more to irregularity of the steel than to chemical errors. It should be noted, therefore, that both plates had been rolled direct from small ingots.

Inasmuch as the value of many investigations in this book depend on the accuracy of chemical determinations, Table 4 will be of interest as comparing the results obtained in the laboratory of the Pennsylvania Steel Company with those of the Pottstown Iron Company. The latter works is chosen on account of the investigations conducted there by W. R. Webster into the physical properties of steel. His work is discussed at length in Chapter XVII, Part II.

Table 4.

Comparison of Chemical Results obtained on the same Steels by the Pottstown Iron Co. and the Pennsylvania Steel Co.

Note.—Steels were made by the Pottstown Iron Co.

Heat No.	Carbon, per cent.			Phosphorus, per cent.		Manganese, per cent.		Sulphur, per cent.	
	P. S. Co. Comb.	P. S. Co. Color.	P. I. Co. Color.	P. S. Co.	P. I. Co.	P. S. Co.	P. I. Co.	P. S. Co.	P. I. Co.
1022	.109	.125	.11	.033	.030	.46	.47	.064	.075
1028	.078	.095	.09	.087 / .089	.110	.23	.26	.069	.090
1043	.090	.100	.10	.044 / .039	.025	.31	.30	.058	.066
1069	.068	.090	.09	.064	.065	.33	.34	.064	.086
1082	.109	.120	.12	.055	.050	.34	.36	.048	.057
1084	.109	.120	.11	.045	.040	.45	.46	.039	.038
1097	.094	.110	.10	.075	.075	.31	.34	.087	.098
1099	.146	.145	.13	.053	.065	.66 / .67	.68	.057	.069
Av.	.100	.113	.106	.057	.057	.39	.40	.061	.072

It will be seen that there is a difference of one point in carbon between the determinations by color and by combustion. This, usually, is of no importance, but in carefully equating the influence of elements, such a difference is of some moment. The manganese agrees very well, being sufficiently accurate for all practical purposes.

The two averages of phosphorus coincide, but the individual records show that this is purely accidental. With three exceptions, the error is not of vital importance, but this is hardly true of heats 1028 and 1043. A comparison of the results throughout the columns shows an erratic character, pointing rather to a general uncertainty than to a pronounced wrong in the chemical system. In sulphur, on the contrary, the dif-

ference seems to be fairly uniform, and the separate items, like the average, indicate a fundamental variation in the manipulation.

The variations in results between different laboratories sometimes becomes a matter of great commercial importance, as shown by G. E. Thackray,* who recites a case where the Cambria Iron Company delivered steel running from .074 to .080 per cent. of phosphorus according to its own determinations, while the buyer's chemist found it to contain from .088 to .110 per cent. Having agreed upon an arbitrator the metal was reported to hold between .063 and .087 per cent.

This experience led to the distribution of drillings from two different pieces of steel to many of the steel works and chemists of the country, and the paper just referred to gives the individual records. In the case of one piece of steel, the lowest phosphorus reported was .045, and the highest .055 per cent. In the second piece, the lowest determination was .076, and the highest .091 per cent. In commenting upon these results, Mr. Thackray considers that they are "quite harmonious" and encouraging, although he acknowledges that they "by no means approach perfection, and leave room for further improvement."

SEC. 6.—*Methods by which metallurgical laws must be deduced.*—If the many causes of error which have been enumerated could be removed, the investigation of the laws that govern the physical qualities of steel would be wonderfully simplified. As it is, the records include inconsistencies and contradictions which are almost appalling. Taking, for example, the apparently simple problem of determining the effect of carbon upon steel, we find in Mr. Howe's book† the following paragraph: "While we can not accurately quantify the effects of carbon upon steel, *I believe* that for ordinary unhardened merchantable steel, the tensile strength *is likely* to lie between the following pretty wide limits:"

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* *A Comparison of Recent Phosphorus Determinations in Steel.* *Atlanta Meeting, A. I. M. E.*, October, 1895.

† *The Metallurgy of Steel*, p. 16.

.05	carbon	between	50000	and 66000	pounds	per	square	inch.
.10	"	"	50000	70000	"	"	"	"
.15	"	"	55000	75000	"	"	"	"
.20	"	"	60000	80000	"	"	"	"
.30	"	"	65000	90000	"	"	"	"
.40	"	"	70000	100000	"	"	"	"
.50	"	"	75000	110000	"	"	"	"
.60	"	"	80000	120000	"	"	"	"
.80	"	"	90000	150000	"	"	"	"
1.00	"	"	90000	170000	"	"	"	"
1.30	"	"	90000	115000	"	"	"	"

The italics are not in the original. They are introduced to call attention to the fact that after leaving out some steels, not merchantable, Mr. Howe *believes* that the limits are *likely* to lie between certain extremes; and these extremes are so far apart, and entangle themselves with one another so confusedly, that the lay mind might well question whether the results were worth recording. Such generalizations were long ago condemned by Bacon in the dictum, "*inductio quae procedit per enumerationem simplicem res puerilis est.*"

The laws of steel can be found only by the comparison of metals which have been made by the same process, analyzed in the same laboratory, rolled under the same conditions, and tested in the same way. With records so collaborated, the deductions are of the highest value, even though the results are not strictly comparable with those of other investigators.

Not only are carefully recorded experiments to be accepted, but much virtue should be accorded the unformulated generalizations of experience. The advances in metallurgical science are seldom due to special investigations. These are usually the exponents, not the causes, of progress, and they refine, rather than create, the methods of procedure. Not one man in a hundred has ever put down on paper a graphic proof that carbon strengthens steel; by long experience that fact was discovered without the plotting of a curve, and without any careful isolation of this element from all confusing conditions.

Running along in the mind of the practical man is a long series of results, some of them complicated with high manganese, some with high phosphorus, some with abnormal rolling, some with erratic analysis; but, just as in the wildest resonance of orchestral music a simple air may ring out clearly above the swelling diapason, so are the fundamental facts of

science seen by the observant mind amid a multitude of accidental conditions, with a clearness which mathematics may not explain.

Such opinions must not be taken as final, but there is a vast difference between proving the truth in a disputed issue and verifying an accepted theory. Most of the experiments given in this book are merely illustrative of laws which are commonly received in the metallurgical world. They try to value the factors whose existence is already conceded. There are many things in the manufacture of steel which we do not understand. There are still improvements to be introduced and discoveries to be made; but the work is all surveyed; the mysteries have been swept away. The making of steel was once a trick; it was then an art; it is now a business.

CHAPTER II.

PIG-IRON.

SECTION 7.—*General outline of blast-furnace practice.*—Three kinds of ore are used in the making of pig-iron, *viz.:* carbonates, magnetites and hematites.

(1) Carbonate ($FeCO_3$), called also blackband, or clayband, or clay-ironstone, contains, when pure, only 48.28 per cent. of iron, and is usually roasted to expel the carbonic acid before being charged in the blast-furnace. In England it constitutes four-fifths of the total ore raised, but in this country, although occurring quite widely distributed throughout the coal measures, it is usually impure and has been driven from the market by richer ores.

(2) Magnetite (Fe_3O_4) contains 72.41 per cent. of iron when chemically pure, and is regarded as a chemical union of the ferrous oxide (FeO) with the ferric oxide (Fe_2O_3). Its distinctive characteristic is its attraction for the magnet, although this property is possessed in slight measure by some varieties of hematites, owing to the presence of small amounts of the magnetic oxide.

The best-known deposits in this country are in New York, Pennsylvania, New Jersey and Michigan.

The New York beds are situated for the most part in the Lake Champlain district, and some of them are rendered valueless by the presence of titanium, which gives an infusible slag in the blast-furnace, no method being known by which its action can be prevented. In Pennsylvania the Cornwall banks are the most important, yielding, with good coke, an iron with not over .04 per cent. of phosphorus, but the sulphur in the ore runs about 2.5 per cent., so that a preliminary roasting is necessary. The run of the mine will scarcely average 50 per cent. of iron, while the silica is about 10 per cent. The copper is the most objectionable feature, occurring in irregular

veins throughout the bed in such quantities that the pig-iron contains about three-quarters of 1 per cent. of this element. This is a serious matter in steel manufacture, for although the copper does no harm in the finished material, it gives rise to hot-shortness and produces many imperfections in rolling.

In New Jersey some deposits containing sulphur have been worked in the past, the ore being roasted before smelting, but the mines are now almost abandoned. Within the last few years the introduction of magnetic concentration has rendered available large deposits of very lean and silicious magnetites, and has given a new lease of life to the beds of this state as well as to those of New York and Michigan.

The great difficulty in this method of concentration arises from the necessity of crushing the ore very fine to free each magnetic particle from the silica, phosphorus and sulphur. The finer it is ground, the purer is the product, but the large proportion of dust gives much trouble in smelting, both by impeding the blast and by flying out the down-take into the stoves. Very recently this trouble has been overcome by making this fine concentrate into bricks, and some of these, made from a phosphoritic and very silicious deposit running from 30 to 40 per cent. in metal, contained only 3.3 per cent. silica, .04 per cent. phosphorus, and 67 per cent. iron. If this series of operations of mining, crushing, concentrating and bricking can be carried on in competition with foreign ores, a tremendous development of the lean deposits of New Jersey and New York may be expected.

(3) Hematite (Fe_2O_3) is the ferric oxide and contains, when pure, exactly 70 per cent. of metallic iron. It occurs sometimes as specular hematite, the fracture presenting a black, shining, crystalline appearance, but often the color is a reddish-brown or yellow, in which case it contains a certain proportion of combined water. The accidental moisture of the ore can be driven off by exposure to a temperature of 212° F. (100° C), but the combined water remains as an integral part of the chemical compound, the percentage of this varying from zero in the specular hematites to over 13 per cent. in the less crystalline varieties. Mineralogists have classified these minerals according to their content of combined water, but it is customary to speak of the purer kinds as

"red" or "brown" hematites, while the more hydrous ores are called "soft" hematites or limonites. This latter term should really be applied only to bog-iron ore containing over 20 per cent. of water, but the above classification has been sanctioned by custom and by the Census Bureau.

The combined water is not a very important agent in the smelting process, but is always a source of expense in other ways, for if it costs $4.00 to put a ton of ore, containing 10 per cent. of water, in the stock-house of a blast-furnace, then 40 cents per ton has been paid for digging, loading and unloading water. If such ore contains only 55 per cent. of iron, it will require 1.75 tons* to make a ton of pig-iron, and the cost of this water will be 70 cents on every ton of product, without counting the heat required to vaporize it in the furnace. Thus this harmless ingredient may make a mine unprofitable which otherwise would be a paying investment. On the contrary, by a slight twist of logic, it may be said that under some conditions the water is a benefit, for with a given content of iron oxide it is far preferable that the foreign matter be water rather than silica or alumina.

Another kind of hematite, known as fossiliferous ore, occurs for the most part in Alabama, and is supposed to have been formed by the action of sulphate of iron upon fossiliferous carbonate of lime. Oftentimes a considerable portion of the limestone remains undecomposed, and the insoluble organic phosphates are a decidedly objectionable characteristic.

Even if carbonate of iron is charged into the blast-furnace in its natural state, the carbonic acid is expelled by the heat and plays no part in the smelting operation, so that all three of the ores just mentioned may be regarded simply as compounds of iron and oxygen, together with earthy impurities.

The ore is dumped into the top of a blast-furnace with two-thirds to three-fourths of its weight of coke. This furnace should be at least sixty-five feet high, and preferably from eighty to one hundred feet, of a form such as is shown in Fig. I. It is kept full of stock, and the combustion of the coke is con-

* In the calculation of the quantity of ore necessary to make a ton of iron, it must be remembered that pig-iron contains carbon, silicon, phosphorus, and other elements, so that even in a very pure, low-silicon pig there will not be over 96 per cent. of metallic iron.

stantly maintained by the introduction of hot blast through the tuyeres at the hearth. Immediately in front of these tuyeres the temperature is very high, but the constant tapping of the liquid products and the constant supply of fresh stock from above prevents this high temperature from spreading upwards, as it would do if nothing were withdrawn from the bottom of the column.

The region which is at a sufficiently high temperature to liquefy the stock is known as the "zone of fusion." It reaches several feet above the tuyeres, the exact extent varying with several conditions of furnace practice. When the oxygen of the blast comes in contact with the coke, it forms either carbonic acid (CO_2), or carbonic oxide (CO), but if CO_2 does form, it is instantly reduced to CO by the next atom of carbon, so that when the gases leave the zone of fusion and travel upward through the stock to the top of the furnace, they may be regarded as a mixture of carbonic oxide (CO) and the nitrogen of the blast.

The CO absorbs the oxygen from the ore, forming CO_2, and leaves the iron in the finely divided metallic state known as "spongy iron." On reaching the lower and hotter parts of the furnace near the zone of fusion, the spongy iron absorbs carbon from the coke, and is thus converted into "pig-iron," which may be regarded as carbide of iron, the percentage of carbon usually running from three to four per cent. The iron also absorbs some silicon, phosphorus, and sulphur from the earthy ingredients of the charge. These probably exist in the pig-iron as silicide, phosphide, and sulphide of iron.

In addition to the coke which is charged with the ore, a certain proportion of limestone is added. The carbonic acid of this stone is expelled in the upper part of the furnace, and caustic lime (CaO) remains. In rare cases the stone has been subjected to a preliminary calcining, but the economy of this practice is not yet demonstrated. The amount of limestone is regulated so that it will satisfy the silica contained in the ore and in the ash of the coke, and give a slag which is sufficiently acid to be liquid and run freely from the furnace, and which is also sufficiently basic to absorb the sulphur from the coke and ore.

At the top of the furnace there is an enormous volume of escaping gas derived from the passage of the blast through the column of burning coke and ore. This is composed of nitrogen, together with some carbonic acid and a larger proportion of carbonic oxide, the percentage of the latter being sufficient to make the mixture available as fuel. Part of this gas is burned under boilers to furnish steam for the blowing engines, while the remainder is used for the preheating of the blast.

Formerly the air was heated by forcing it through iron pipes which were surrounded by burning gases, but of late years it is the almost universal practice to have a set of brick stoves, filled with long narrow passages. By passing burning gas through a stove for an hour or more, the bricks are heated to a high temperature, whereupon the air is blown through in an opposite direction and is heated to nearly the same point. The stoves are used alternately, so that by means of suitable valves the action is practically continuous. In well-equipped furnaces the temperature of the blast is maintained between 1000° F. and 1200° F., these figures being often exceeded under favorable conditions.

SEC. 8.—*The American iron industry.*—The distinctive feature of the American iron industry in recent years has been the development of great deposits of red and brown non-hydrous hematites in the Lake Superior district, which now produces one-half of all the ore mined in the country. They are of exceptional richness, running sometimes over 67 per cent. in iron, equivalent to nearly 96 per cent. of Fe_2O_3, with only 2 per cent. silica, and most of them are sufficiently free from phosphorus to be suitable for the manufacture of steel by the acid process.

In former days it was the rule to place the blast-furnace near the ore mines, but this system is passing away. The furnaces of Johnstown, Pa., built to smelt the ores in the hills that environ them, draw their supply from the mines of Lake Superior, while the quarries of Southern Cuba deliver their product to the valley of the Susquehanna. The main points of the geographical distribution of the iron industry were ably presented by John Birkinbine in his presidential address to the American Institute of Mining Engineers in June,

1892.* He shows that in 1890, when our pig-iron production reached high-water mark, 69 per cent. of the Bessemer iron and 64 per cent. of all kinds of iron were made in 4 districts. In Table 5 the figures for that year are compared with the record for 1894, when the entire country was overwhelmed by an industrial and financial cyclone. The comparison will serve to show the change in relative production when disastrous prices had forced the least favored manufacturers to the wall.

TABLE 5.

Production of Pig-Iron in the United States by Districts; gross tons.

District.	Bessemer Iron.			All Irons.		
	1890	1894	Last six months of 1894	1890	1894	Last six months of 1894
Pittsburg district,	1,336,307	2,040,552	1,208,319	2,430,931	2,596,515	1,575,136
Eastern Pennsylvania,	876,266	439,712	274.157	1,973,148	818,058	469,686
Illinois,	628,863	543,309	347,165	701,106	604,795	388,674
Alabama,	none	none	none	816.911	592,392	336,442
Total in four districts,	2,841.436	3.023.573	1.829,641	5,922,096	4,611,760	2,769,938
Total in United States,	4.092,343	3,808,567	2,307,080	9,202,704	6,657,388	3,939,405
Per cent. of total output in Pittsburg.	33	53	52	26	39	40
Per cent. of total output in Eastern Pa.,	21	12	12	21	12	12
Per cent. of total output in Illinois,	15	14	15	8	9	10
Per cent. of total output in Alabama,	. . . . .	. . . . .	. . . . .	9	9	8.5
Per cent. of total output in four districts,	69	79	79	64	69	70.5

The Pittsburg district includes Allegheny County, Pa., the Shenango Valley, Pa., and the Mahoning Valley in Ohio. The first furnaces of this region were started on local ores, principally carbonates, but now almost the entire supply comes from Lake Superior, 600 to 1000 miles away. The magnificent development of this center of production is due in great measure to its being within easy reach of the coke of Connellsville, which ranks with the best in the world.

Eastern Pennsylvania includes the Lehigh, Schuylkill and Susquehanna valleys, which were developed on local brown hematites and the magnetites of Cornwall, Pa., New Jersey, and Southern New York, aided by the proximity of the anthracite coal fields. In later years the use of coke has increased throughout the district, and there has been a con-

* *The Influence of Location upon the Pig-Iron Industry. Trans. A. I. M. E.*, Vol. XXI, p. 473.

stantly increasing importation of foreign ores. The future of this region lies in the removal of the duty upon iron ore and the economical success of magnetic concentration. The Cornwall deposit is an important factor, but its high sulphur and copper, and its non-adaptability to concentrating treatment, will render its position less commanding than in the past.

The Illinois district is composed for the most part of the furnaces at Chicago, which draw their ores from Lake Superior and their coke from Connellsville, distances varying from 300 to 650 miles, and which depend for their existence on exceptional railroad and water facilities and a home market.

The Birmingham district in Alabama has certain great advantages, for there are few places in the world where fuel and ore are so near together, although, unfortunately, both are of inferior quality, the ore being low in iron and high in phosphorus, and the coal giving a weak and impure coke.

SEC. 9.—*Fuel consumption in American blast-furnaces.*—In the foregoing remarks it has been assumed that coke is the fuel employed, and this is true for the overwhelming majority of furnaces, for, although anthracite coal is sometimes used from economic considerations, and although it may give excellent results when it constitutes only a part of the fuel supply, it is found that much more satisfactory practice is attained when coke forms at least a portion of the charge. It is customary to classify as an anthracite furnace one which only occasionally uses anthracite in its mixture, so that statistics on this point are somewhat misleading.

There are also some furnaces which use charcoal exclusively, since this is supposed to give an iron which is especially valuable in making car wheels and other articles where great toughness must be combined with great resistance to wear. Its superiority over other irons of exactly the same ultimate chemical composition is widely disputed as an antiquated theory, but the testimony in favor of this theory is too strong to be set aside.

Fifteen years ago the practice at almost all blast-furnaces was regulated by a "rule of thumb," which was generally born of a bigoted belief on the part of an ignorant furnaceman that the particular ores and fuel under his control could be worked only in a furnace of certain special lines, and that

it was impious to "drive" beyond the certain rate established by time-worn tradition. In 1879 certain experiments were instituted at the Edgar Thomson Steel Works, which showed the possibility of enormously increasing the output of a furnace by increasing the amount of air supplied to the tuyeres, and the effect of this discovery was immediately seen in the vigorous blowing and forcing of the furnaces of other plants, and the building of new furnaces at Braddock with an enormous blowing equipment. There was also introduced the radical and revolutionary idea that the pressure on the tuyeres was not the true guide by which to regulate the blast, but that a certain quantity of air should be delivered to the furnace, whether the resistance of the stock was great or small.

Under the system of rapid driving, it was thought advisable to make the angle of the bosh about 80°, in order that the descent of the stock should not be interrupted, and so from 1880 to 1885 there was a race between rival managers to eclipse the tonnage records of their fellows. It was soon discovered, however, that this system gave a heavy consumption of fuel per ton of product, for the ore did not stay in the upper part of the furnace long enough to be thoroughly reduced, and part of it was carried down to a zone of higher temperature where CO_2 absorbed carbon from the fuel.

SEC. 10.—*Chemical reactions in the blast-furnace.*—The reactions between mixtures of Fe_2O_3, CO, CO_2 and C, are quite complicated and vary with changes in temperature and extent of exposure, so that it may happen that a mixture of CO_2 and CO, which can reduce Fe_2O_3 at a low red heat, will oxidize spongy iron at a higher temperature.

It may be assumed that the presence of CO_2 in the tunnel-head gases is almost entirely due to the burning of CO by the oxygen of the ore. The reduction of the ore should take place in the very top of the furnace where the temperature is below that at which CO_2 and C unite; but if time enough is not given, some of the reduction occurs lower down in the furnace, where the temperature is higher, and some CO_2 is immediately converted into CO by the coke. The carbon so absorbed and carried away in the escaping gases must be looked upon as wasted, except as far as it is utilized under the boilers or in the stoves,

and it may be taken as a rule, therefore, that the economy of a furnace is proportional to the percentage of CO_2 at the tunnel head. It is impossible to obtain perfect results, for it is only the loosely held oxygen which parts company with the ore at very low temperatures, and Bell* states that in smelting Cleveland ore, 25 per cent. of the oxygen is retained until the region of the tuyeres is reached; and he also says† that the greatest extent to which we may assume it possible to oxidize the carbon as a whole, is so as to have one unit of this element escaping as carbonic acid and two as carbonic oxide.

SEC. 11.—*Modern improvements in blast-furnace practice.*—The heavy consumption of coke which followed the first attempts at rapid driving was not as serious a matter in the Pittsburg district as in localities where coke was more costly. A reform was inaugurated by E. C. Potter, of Chicago, who showed‡ that by a somewhat less volume of blast and by a reduced angle of bosh, the product was only slightly reduced, while the coke consumption was cut down by a very considerable amount. Great advantage also accrued from an enlargement of the hearth, but the further suggestion that the bosh-angle could be increased with a wider crucible has been found impracticable.

The whole subject of modern blast-furnace practice was discussed by Gayley, of The Edgar Thomson Steel Works, Pittsburg, Pa.,§ before the Mining Engineers, and drawings were given of the furnaces at that works. The last form described is shown in Figure I, and there has been very little change in later practice. It is stated, in the paper just mentioned, that this furnace produced 225,000 tons from one lining, with a fuel consumption of 1920 pounds of coke per ton of iron. Later practice has improved upon this record, but this has been by careful attention to details, rather than by any special change in essentials. Prominent among these determining conditions is the preservation of the lines of the

* *Trans. A. I. M. E.*, Vol. XIX, p. 960.

† *Manufacture of Iron and Steel*, 1884, p. 96.

‡ *The South Chicago Works of the North Chicago Rolling Mill Co.*, *Journal I. and S. I.*, Vol. I, 1887, p. 163.

§ *The Development of American Blast-Furnaces with Special Reference to Large Yields. Trans. A. I. M. E.*, Vol. XIX, p. 932.

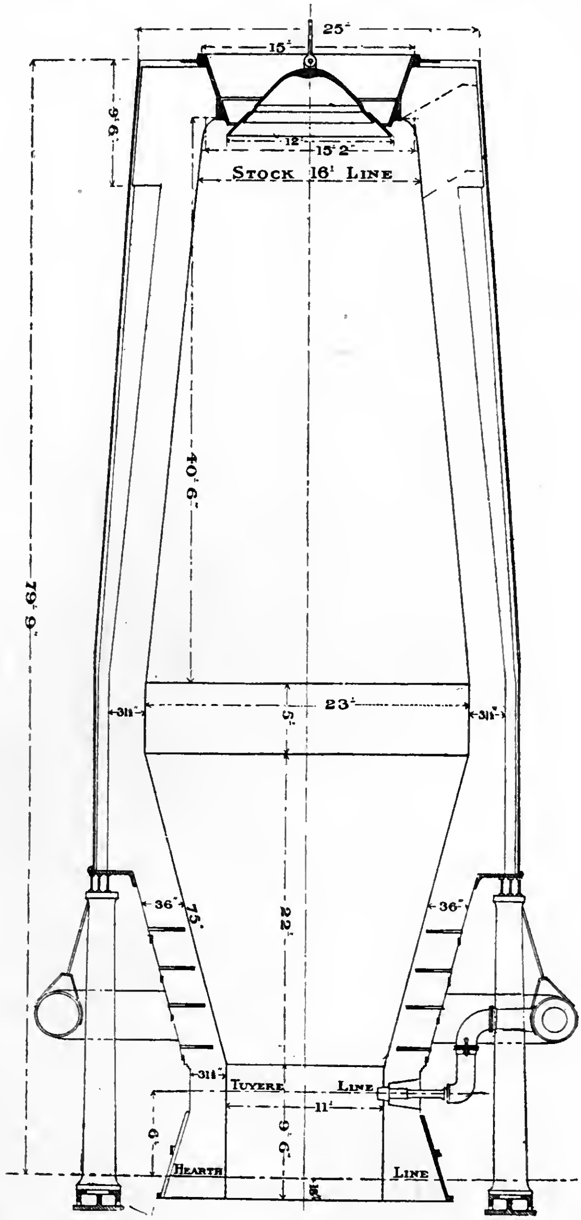

Fig. I.—Type of Blast-Furnace Used at the Edgar Thomson Steel Works.

bosh by numerous water-cooled blocks. It is also necessary that there shall be a large reserve capacity for heating the blast, so that a maximum temperature is retained nearly uniformly throughout the period between reversals, the working conditions of temperature being thus entirely under control.

By a constant strengthening of every weak point in practice, the life and output of a furnace have been increased far beyond what only a few years ago was deemed the limit of hope. The last information* from Edgar Thomson is of a furnace which has made 660,000 tons of pig-iron in a campaign of five years, and which is still in blast. This magnificent record is due in great measure to the working factors just enumerated, but the unequalled richness of the Lake Superior deposits and their porous character, rendering them capable of rapid reduction, are the fundamental conditions which make the result possible. Many furnacemen, in a small way, are doing fully as good work, although they can not show the big totals of clean product in a given time. In the discussion of Gayley's paper just mentioned, some engineers tried to make detailed comparative calculations on relative sizes and products, but such figures are of little value, for he who does well with little things does not always rule well over bigger things. Nevertheless, it must be recognized in a general way that many furnaces, running on impure ores and fuel, require more attention and more study than is needed for the production of the remarkable tonnages which appeal so strongly to American pride.

SEC. 12.—*Differences in local conditions as affecting fuel economy.*—The great difference between the conditions in two different districts was well brought out by Sir Lowthian Bell in the consideration of Gayley's essay. The examples taken were the Cleveland district in England, where the ore does not contain over 42 per cent. of iron, and the Pittsburg region, where it runs at least 60 per cent. The detailed investigation is given in Tables 6 and 7.

In these tables there are some changes made from the figures given in *Trans. A. I. M. E.*, Vol. XIX, p. 959, for in the

* Private communication, January, 1896.

TABLE 6.

Comparison of Blast-Furnace Practice at Cleveland (England) and Pittsburg.

Working Conditions.	Cleveland.	Pittsburg.
Cubic contents of furnace, feet	25500	18200
Temperature of blast, degrees cent.	704	593
Coke consumed per ton of iron, pounds	2239	1882
Limestone consumed per ton of iron, pounds	1232	1011
Ore consumed per ton of iron, pounds	5376	3613
Weight of blast per ton of iron, pounds	9761	7974
Weight of gases per ton of iron, pounds	13381	11211
Temperature of gases, degrees cent.	250	171
Weekly product per 1000 ft. cubic content, tons	21.57	128.00
Slag produced per ton of iron, pounds	3136	1200
Calories	88577	69569
Calories developed per unit of coke	4431	4141

TABLE 7.

Distribution of Calorific Power in Cleveland and Pittsburg Blast-Furnace Practice.

Heat Requirements.	Per Ton of Pig-Iron.			
	Cleveland.		Pittsburg.	
	Calories.	Equiv. in coke, lbs.	Calories.	Equiv. in coke, lbs.
Reduction of peroxide of iron	33108	837	33108	896
Reduction of metalloids in pig-iron	4174	105	2631	72
Dissociation of carbonic oxide	1440	37	1460	39
Fusion of pig-iron	6600	167	6600	178
Evaporation of water in coke	275	7	83	2
Decomposition of water in blast	2380	60	2333	63
Expulsion of CO_2 from limestone	4070	103	3094	84
Reduction of this CO_2 to CO	4224	106	3488	94
Fusion of slag	15400	390	5890	159
Carried off in gases	7166	179	5013	136
Lost by radiation, convection, tuyere-water, etc.	9740	248	5869	159
	88577	2239	69569	1882

original the second and fourth columns should be headed hundredweights instead of pounds. Strictly speaking, the figures are comparative and not absolute, but I have calculated them into pounds to make them intelligible to American readers. I have also corrected an error of transposition, for in the original the figure 1.42 should be opposite 5890 and .84 should be on the line with 3488.

It will be seen that there are many items here which are beyond the control of the metallurgist, depending as they do on the impurities of the ore and on the required limestone. The most important of these are given in Table 8.

TABLE 8.

Blast-Furnace Factors Depending on Impurities in Ore and Stone.

Factor.	Value in Pounds of Coke.		
	Cleveland.	Pittsburg.	Difference.
Reduction of metalloids.	105	72	33
Expulsion of CO_2 from limestone . . .	103	84	19
Reduction of this CO_2 to CO	106	94	12
Fusion of slag	390	159	231
Totals	704	409	295

Thus, while the total difference in favor of Pittsburg practice is 357 pounds of coke per ton of iron (as shown in Table 6), the above comparison shows that 295 pounds are entirely beyond the control of the Cleveland smelter.

In addition to these necessary increments of fuel consumption, there are certain difficulties introduced with every pound of foreign material. More especially when a high content of sulphur calls for the creation of an extra-basic cinder, but none the less truly when the impurities are less potent for evil, it is plain that the management of a furnace must be more difficult when a large quantity of dirt interferes with the operations, and it follows, therefore, when all other things are equal, that the furnace will more often suffer from those slight attacks of illness which go so far in determining the fuel ratio of the campaign.

SEC. 13.—*Effect of the impurities of the ore and the fuel upon the furnace practice.*—Aside from the mere volume of foreign matter in ore and coke is the still more vital question of their character. The common and well-nigh universal impurities are alumina, magnesia, lime, phosphorus, silica and sulphur. The lime is usually a benefit, for it saves the addition of a corresponding quantity of limestone. The magnesia is usually considered less desirable, but is deemed beneficial by some metallurgists, provided alumina is absent.* The phosphorus has no appreciable effect on the running of the furnace, but under all ordinary conditions it is almost all reduced and alloyed with the iron. The function of alumina

*See Firmstone; *Magnesia and Sulphur in Blast-Furnace Cinder. Trans. A. I. M. E.*, Vol. XXIV, 498 and 889.

is not thoroughly understood. It is stated by Elbers * that "if the percentage of silica is low, it acts as an acid and hence increases the fluidity of the slag, but if high, it acts as a base and lowers the fusing point." The exact equation of alumina has not been written, but it is usually regarded as an objectionable component of the charge, save in the case of titaniferous ores, when it may be advantageous by furnishing an additional component of the slag and thus augmenting the fluidity by increasing the complexity of the compound.

The silica occurs in the ash of the coke and also in the ore, either free or in combination with alumina, magnesia, lime or iron, and necessitates the addition of a proportional quantity of lime. The coke varies greatly, but a fair average of Connellsville product will show from 10 to 13 per cent. of ash, the greater part of which is silica. The ore of some of the Lake Superior deposits runs as low as 2 per cent. in silica, but in less favored districts three times this amount is considered a fair content, while some well-known beds of Cuba and Spain run about 10 per cent.

A certain amount of silica is reduced by the gases and the silicon unites with the pig-iron, the extent of this reaction depending on several conditions, being aided by:

(1) A rise in temperature; for at high thermal altitudes, the oxygen has a greater affinity for carbon than for silicon, and, therefore, carbon can reduce silica with production of silicon.

(2) A decrease in lime additions; for lime tends to hold silica in proportion to its needs, so that the higher a slag is in silica, the less firmly is any one molecule fastened in that slag.

(3) An increase in the total amount of silica present; for, when all other things are equal, the greater the exposure, the greater is the opportunity for its reduction, so that if one furnace working on ores low in silica makes three-quarters of a ton of slag to every ton of iron, and another furnace working on ores high in silica makes one and one-half tons of the same composition, the tendency will be toward twice as high a silicon content in the second pig-iron as in the first.

* *Berg- und Hüttenmännische Zeitung*, Vol. XLVII, p. 253.

SEC. 14.—*Metallurgical conditions which influence the character of the product.*—It often happens that the effect of two or more factors in furnace work are contradictory, for it is not uncommon to have a high temperature combined with a limey slag in the production of low-silicon iron free from sulphur.

Sulphur sometimes exists in the ore up to one-half of 1 per cent., and in exceptional cases it is over 2 per cent., but usually the greater part of this element comes from the coke, which may contain over 2 per cent. and seldom has less than one-quarter of 1 per cent. The removal of this metalloid may be accomplished by a limey slag and a hot furnace, it being generally found that it is easier to take care of a given quantity of sulphur from the coke than from the ore. It has been stated that a high temperature aids in the reduction of silicon by certain peculiar laws of chemical affinities, but it is doubtful whether there are any such reversed relations in the case of sulphur, although a high temperature is necessary in order that a limey slag may be kept fluid and exert its full effect.

It will be noticed that one of the conditions assisting in the elimination of sulphur, *viz.:* high temperature, is also favorable for the reduction of silicon, while the other condition—a basic slag—is opposed to it. This complication gives rise to variations in practice whereby these factors are arrayed against each other for the attainment of certain ends. Thus it is possible to make:

(1) An iron with high silicon and low sulphur, by running the furnace at a high temperature with a slag sufficiently basic to hold the sulphur, but not basic enough to keep silicon from being reduced.

(2) An iron with low silicon and low sulphur, by using a lower temperature with a somewhat more basic slag, or a high temperature with a much more basic slag.

(3) An iron with low silicon and high sulphur, by using a low temperature with a slag not sufficiently basic.

(4) An iron with high silicon and high sulphur, by using a high temperature with a slag not sufficiently basic.

Manganese is another element which is found in many ores, and which occasionally plays an important part in the opera-

tion. A content of only 1 or 2 per cent. in the ore will nearly all be carried away in an ordinarily acid slag, but if a greater quantity of lime be added, there is less demand for metallic oxides in the cinder and the manganese is reduced and alloyed with the iron. A high temperature seems to favor this reaction, but part of this effect may be due to the corresponding increased fluidity in the extra-basic slag.

The specifications of high temperature and a limey slag, which favor the presence of manganese in the pig-iron, tend also toward the elimination of sulphur. When the slag is made very basic, as it should be in the production of spiegel to prevent the loss of oxide of manganese in the cinder, the conditions are evidently opposed to the reduction of silicon, so that high-manganese iron generally contains low silicon, and almost always low sulphur. It is possible, however, by special care, to make a silico-spiegel containing as much as 11 per cent. of silicon and 18 per cent. of manganese, this alloy being used as a recarburizer in steel-making.

Sec. 15.—*Discussion of blast-furnace slags.*—It is easy to make broad statements concerning the general effect of acid and basic slags, but it is quite another thing to define the limits which determine practice. Thus, in smelting the pure ores of Lake Superior, a slag of 35 per cent. of SiO_2 and 40 per cent. of CaO might be amply capable of removing all the sulphur, while to make as pure an iron from the sulphurous ores of Cornwall will require a reduction of 5 per cent. in the silica and a corresponding increase in the lime.

Magnesia has been proclaimed by high authority to be an evil (see Ledebur, *Kaernthner Zeitschrift*, No. 2, 1881, p. 53, *et seq.*, *et als.*), but there are reasons for supposing that it has not had a full hearing. A paper by Firmstone* discusses this question, and it is decided that magnesia is harmful only when the alumina is high. This will also be evident from the analyses of Pennsylvania Steel Company cinder in Table 9.

This gives the composition of different slags, the data being culled from various sources, which will illustrate how widely the composition may vary, and that differences in furnace

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* *Magnesia and Sulphur in Blast-Furnace Cinder. Trans. A. I. M. E.*, Vol. XXIV p. 498.

temperature are fully as potent as the cinder in determining the composition of the iron.

SEC. 16.—*Appearance of the fracture of pig-iron.*—The three elements, silicon, sulphur and manganese exert an important influence on the appearance of the fracture of pig-iron owing to the variations they cause in the chemical status of the carbon. If a normal pig-iron, made from a furnace working at a moderately high temperature, is allowed to cool slowly, the carbon separates and the entire mass is permeated

TABLE 9.

Analyses of Blast-Furnace Slag.

No. of Sample.	Composition, per cent.						Authority.
	Slag.				Iron.		
	SiO_2	Al_2O_3	CaO	MgO	Si	S	
1	31.75	23.75	43.75	....	2.75	.03	French works, *Journal I. and S. I.*, Vol. I, 1891, p. 362.
2	29.75	21.75	47.75	....	.75	.05	
3	29.75	22.75	46.75	....	.40	.06	
4	28.25	22.25	49.75	....	.35	.03	
5	36.60	17.85	38.44	....	.50	.35	
6	32.73	9.51	33.84	17.08	....	....	Fackenthal, *Trans. A. I. M. E.*, Vol. XXI, p. 348.
7	28.50	20.00	28.50	22.00	2.00	.05	Potter, *Journal I. and S. I.*, Vol. II, 1887, p. 170.
8	35.70	16.31	24.75	18.67	white		*Journal I. and S. I.*, Vol. II, 1891, p. 249.
9	44.67	20.48	24.98	2.40	white		
10	43.70	10.40	23.54	13.17	white		
11	33.25	12.17	31.26	12.93	grey		
12	40.95	8.70	30.35	16.32	grey		
13	33.10	14.92	40.76	9.67	3.37	tr.	Penn'a., Steel Co., hot furnace.
14	32.27	14.57	41.02	10.30	3.18	tr.	" " " " "
15	34.26	11.53	40.25	13.28	4.81	.01	" " " " "
16	32.68	13.50	43.28	9.44	1.25	.06	" " " not so hot.
17	32.28	9.38	46.95	9.52	0.70	.11	" " " slightly cool.
18	34.50	7.94	46.47	10.47	0.69	.05	" " " fairly hot.

by black shining crystals of graphite, while on the other hand if the iron is suddenly chilled after casting, this separation is prevented and the carbon remains combined as carbide of iron, the fracture showing a clear white surface. The silicon, sulphur and manganese interfere in this simple relation without completely overturning it, so that it is difficult to say in any particular case whether a given appearance is caused by the chemical composition, or by the furnace history that gave birth to that composition.

Iron with 2 or 3 per cent. of silicon usually has a graphitic fracture, and this could be due to the high furnace temperature which usually accompanies the production of high silicon,

but it is probable that silicon has an influence of its own, for it is found that in irons with a content of 20 per cent. silicon the carbon is mostly graphitic, and according to Hadfield* is always under 1.5 per cent. and often under 0.75 per cent., and this indicates that silicon drives the carbon out of combination. Experiments by Keep† seem to show that silicon confers greater strength and toughness up to a content of 2 per cent., this being due to the fact that when the silicon is low, the carbon remains combined, producing a brittle and unsound casting. Keep also states (*loc. cit.*) that the increased fluidity accompanying high silicon is not due to any direct effect of the metalloid *per se*, but to its property of driving the carbon into the free state.

Sulphur exerts an opposite influence, so that iron with a high percentage—say over 0.20 per cent.—is quite certain to be of close fracture. Manganese has the same effect as sulphur, and, when the metal contains 4 or 5 per cent., the broken surface is quite sure to be white, and lesser quantities have their proportionate influence. In irons with high manganese the tendency to force the carbon into combination is so powerful that there is a marked increase in the total percentage of the latter metalloid.

With varying casting-temperatures and different percentages of the three elements, it is impossible to predict the nature of every corresponding fracture. The necessity for this is in some measure passing away, for it is by chemical rather than by physical constitution that iron is valued, but in comparing irons made from the same ores and by the same methods, the fracture is a valuable exponent of the chemical equation. Table 10 will give a general idea of the composition of the different grades of pig-iron, and the data on the silico-spiegels will show how silicon crowds out carbon, while the ferro-manganese will illustrate the absorption of carbon with increase in manganese.

SEC. 17.—*Physical specifications for cast-iron.*—The common requirements for structural cast-iron are summarized by A. E. Hunt‡ as follows:

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* *On Alloys of Iron and Silicon. Journal I. and S. I.*, Vol. II, 1889, p. 223.

† *Silicon in Cast-Iron. Trans. A. I. M. E.*, Vol. XVII, p. 683.

‡ *On the Inspection of Materials of Construction in the United States. Journal I. and S. I.*, Vol. II, 1890, p. 300.

"All cast-iron used in compression must be of best quality, tough, gray iron, and must be able in bars 1 inch square and 5 feet long, and when supported by knife edges 4 feet 6 inches apart, to carry a load of 500 pounds, applied at the centre, without rupture and without a deflection of more than 2 inches."

TABLE 10.

Composition of Various Pig-Irons and Spiegels.

No. of Sample.	Chemical Composition, Per Cent.							Kind of Iron.	Authority.
	Fe	Graphite.	Comb. Carb.	Si	P	S	Mn		
1	92.37	3.52	0.13	2.44	1.25	.02	.28	No. 1 Gray,	Hartman, *Jour. Frank. Inst.*, Vol. CXXXIV, p. 132.
2	92.31	2.99	0.37	2.52	1.08	.02	.72	No. 2 Gray,	
3	94.66	2.50	1.52	.72	.26	tr.	.34	No. 3 Gray,	
4	94.48	2.02	1.98	.56	.19	.08	.67	Mottled,	
5	94.68	....	3.83	.41	.04	.02	.98	White,	
6	...	....	4.27	1.10	...	..	8.11	Spiegel,	Hadfield, *Journal I. and S. I.*, Vol. II, 1889, p. 226.
7	...	....	4.78	.52	...	..	19.74	"	
8	...	....	5.63	.42	...	..	41.82	Ferro-manganese,	
9	...	....	6.53	.97	...	..	80.04	"	
10	...	....	7.20	.14	...	..	80.04	"	
11	...	....	3.56	4.90	...	..	23.90	Silico-spiegel,	
12	...	....	2.56	4.20	...	..	50.00	"	
13	...	.33	1.85	10.74	...	..	19.64	"	
14	...	.67	.98	12.60	...	..	19.74	"	
15	...	.90	.30	15.94	...	..	24.36	"	
16	...	2.35	.05	8.77	...	..	2.42	Ferro-silicon,	
17	...	1.85	.06	11.20	...	..	2.78	"	
18	...	1.20	.23	14.00	...	..	1.95	"	
19	...	.55	.11	17.80	...	..	1.07	"	

The use of gray iron is important, since it is much less liable to break under shock than white iron, but, although this is true as a general rule, there is no certainty that such an iron is tough, for it may contain a large percentage of phosphorus, and since this element makes the iron run fluid, there is a constant temptation to use it and thereby produce a brittle metal.

The international conferences on uniform methods of procedure in testing structural material have passed resolutions recommending the following rules for universal adoption in the examination of cast-iron.*

(1) Test-pieces are to be in the shape of prismatic bars, 43 inches long, and have a section of 1.18 inch square. They should have an addition on one end, 1 inch square, from which 1-inch cubes for compression tests can be cut when desired.

* Appendix V to the Report of the Committee on Standard Tests of the Am. Soc. of Mech. Eng., 1893.

(2) These test-pieces are to be cast in a position slightly inclined, rising from one end of the bar to the other. The inclination of the flask is to be one in ten.

(3) The head of pressure under which the test bars are to be cast is to be equal to a gate 8 inches high above the opening.

(4) Dry sand molds are to be used.

(5) During the test the points to be determined are as follows:

(*a*) *Resistance to flexure and work done during bending* up to the point of rupture, using three test-pieces.

(*b*) The *tenacity* as determined from turned test-pieces .785 inch diameter and 7.85 inches long, cut from the two ends of the test-piece broken by flexure, and two of these out of each of the three first tested.

(*c*) *Compression*, determined from cubes 1.18 inch on each side, cut from pieces obtained by *a*, and two such out of each bar. Pressure to be applied in the direction of the axis of the original bar.

(6) The bars for bending, and the cubes for compression test, are to be tested as taken from the sand with the scale on.

(7) Special cast pieces, such as bearing plates for bridges, water pipes, etc., are to be submitted to special test in accordance with the uses to which the pieces are to be put.

These specifications ignore the chemical composition of the metal, and they also take no account of the size of the casting to be made. Much light has been shed upon these two points by a paper published in June, 1895, by W. J. Keep,* who has done so much in the study of cast-iron. The important conclusions of this paper are summarized below, the original wording being preserved as far as possible.

(1) Large test-bars are weaker with each increase of silicon, while small bars, as for instance about one-half inch square, are stronger.

(2) A small casting grows stronger with each increase of silicon, at least up to 3 per cent.

(3) The record of one size of test-bar can not indicate the strength of another size, for the reason that with the same

* *Transverse Strength of Cast-Iron. Trans. A. S. Mech. Eng.*, Vol. XVI.

iron, aside from the local causes of derangement, any change in size, or, in other words, any change in the rate of cooling, will change the grain and strength. Each mixture of iron and each percentage of silicon will produce the best results in some one single size of casting, and not as good a result in any other size.

(4) The metal is strong according as its grain is close and fine, and this is governed by the percentage of silicon and by the rate of cooling, and by local conditions over which the founder has no control.

(5) It is the universal opinion that strength is mainly due to the combined carbon which the casting contains, and that weakness is caused by changing it into graphite, which mechanically separates the grains, but the nineteen series of bars under investigation show that combined carbon weakens castings and never strengthens them, the decrease in strength of large castings being wholly due to loosely united crystals and not to any change in the proportion of combined or graphitic carbon.

(6) Combined carbon may decrease as castings are larger, but the strength always decreases. This decrease of combined carbon and of strength are both caused by the slow cooling, and the decrease of combined carbon has nothing to do with the decrease of strength.

(7) The general opinion is that graphitic carbon causes weakness. The carbon in a casting, so far as has been proved, is either combined or graphitic. If one decreases, the other must increase; therefore, if combined carbon produced strength, the same facts that seemed to warrant this conclusion of the chemists seemed to prove that graphitic carbon produced weakness. Again, in graphitic iron the grain was coarse, and the flakes of graphite lay between the grains, and it seemed self-evident that these graphitic flakes must of necessity separate the grains of iron and cut the casting up, but the same proof that has been produced in the case of combined carbon, to disprove the accepted opinions, will apply regarding graphitic carbon. Strength or weakness seem to be absolutely independent of free carbon, for the looseness of the grain, produced by slow cooling, so separates the grains that there seems to be more than enough room for the flakes of graphite

to lie in the open spaces. It may be even doubted if the graphite ever gets between the grains to make their union less perfect.

(8) The effect of variations in the total content of carbon is not known, on account of the difficulty of making laboratory experiments where this one element varies and where the rest of the composition is uniform. It will not answer to add wrought scraps, for this will not only decrease carbon, but at the same time the percentage of every other element; and also because such scrap will close the grain and increase strength, independently of the lessening of the carbon.

(9) The universal opinion seems to be that sulphur is a damage to cast-iron, but the present series of tests seems to show no ground for this belief, since samples which contain about as high a content of sulphur as is ever found in gray castings show both small and large castings beyond reproach.

CHAPTER III.

WROUGHT-IRON.

SECTION 18.—*General description of the puddling process.*— When pig-iron is melted on a hearth of iron ore and is exposed after fusion to the continued action of the flame, there is a rapid oxidation of the metalloids contained in the iron. The silicon, manganese, sulphur and phosphorus unite with oxygen and iron oxide to form a slag, while the carbon escapes with the products of combustion as carbonic oxide and carbonic acid. By the departure of these alloyed elements, the iron becomes very much less fusible, and when the operation is conducted in an ordinary reverberatory furnace the heat is not sufficient to keep the mass liquid. It first becomes viscous, then pasty, and finally is worked into balls, taken from the furnace, and squeezed or hammered into a bloom fit for rolling.

The crude puddle-ball, when drawn from the furnace, is made up of an innumerable number of globules of nearly pure iron, while the interstices between the particles are filled with slag. By the action of the squeezer much of this slag is expelled, and each subsequent rolling removes a further quantity, but it is impossible to get rid of all the cinder, and it forms a skeleton which permeates the entire mass of the finished bar, forming planes of separation between the particles of metallic iron.

It is unnecessary to say that these films must weaken the material by destroying the continuity of the structure and the cohesion of the particles, and in this respect the slag is an injury.

In other ways it is of incalculable benefit, for the sulphur and phosphorus are never entirely removed in the process of puddling, and there is usually a sufficient percentage of them

left in the product to give bad results if they were able to exert their full effect in producing crystallization, but the network of slag prevents in great measure the tendency to crystallize and thus allows the presence of a considerable proportion of these elements. If bar-iron be melted in a crucible, the slag separates and the impurities have a chance to exert their full force. Some pure irons will successfully undergo this test, but most brands, including many of high reputation for quality, give a perfectly worthless metal after fusion, owing to the high percentages of impurities they contain. The quality of the finished metal, therefore, is not entirely dependent upon its composition, but upon the way in which it has been heated and worked.

The piece of iron made in the first rolling of the puddle-ball is a rough, crude product known as muck bar. For the making of merchant iron, this intermediate product, together with miscellaneous wrought-iron scrap, is bundled into "piles" so as to give a bloom of proper sectional area, and this, after being heated to a welding heat, is rolled into the desired shape. If the pile were square and were made up of similar pieces of equal length, each layer being at right angles to the one below, and if the bloom were rolled equally in each direction, it is evident that the plate would be as strong in the line of its length as of its breadth; but as the bars from which the pile is formed have been made by stretching the material in one way, and as all practical work requires a piece of greater length than width, it will be seen that the finished product will show much better results when tested in the direction of its length than of its width. The result will also depend upon the skill with which the pile has been constructed, upon the perfection of the welding as influenced by the heating and the rapidity of handling, and upon the freedom of the iron from thick layers of slag.

SEC. 19.—*Effect of silicon, manganese and carbon upon the operation of puddling.*—Aside from these important considerations of content of slag and amount of work, the character of the product will depend upon its chemical composition, and this in turn depends upon the composition of the pig-iron from which it is made and upon the care and skill with which the operation has been conducted. There are five elements com-

monly found in pig-iron which have an important bearing on the character of the finished material and on the work of puddling, and these will be considered separately.

Silicon.—This element is present to greater or less extent in all pig-irons, and may be regarded as an almost unmitigated evil, since its oxidation produces silica and this is just what is not wanted to produce a basic slag. Moreover, its union with oxygen does not form a gas, and during its elimination the bath lies dead and sluggish. It is true that metallic iron is set free by the absorption of oxygen from the ore, but this gain is more than offset by the iron oxide which is held prisoner by the silica. Some silicon is oxidized during the melting, so that, with a low initial percentage in the iron, the boil begins very soon after melting. With workmen accustomed to high silicon iron, there is danger of considerable waste in using a lower grade, because the latter melts at a higher temperature, and, since there is not enough silica produced from the portions first melted to give a proper quantity of slag, the bare metal is exposed after melting to a hot flame, with the result that copious fumes of iron oxide escape to the stack. The same trouble is sometimes experienced in changing from a pig-iron which has been cast in sand to one which has been cast in chills, but careful practice has shown that this loss in both cases can be avoided by regulating the operation so that all the iron is melted at one time, and by keeping the metal covered with a fluid cinder, better results being obtained, both in time and waste, than with an iron containing a higher percentage of silicon, or one which carries a quantity of adhering sand.

Manganese.—Although acting in the same way as silicon in giving a dead bath, manganese is not quite as objectionable, for its oxide is a base which replaces and saves an equal quantity of iron oxide, and it also aids in the elimination of sulphur.

Carbon.—Unlike silicon, which varies in different forge-irons from 0.25 to 1.25 per cent., and manganese, which is present in all proportions from a trace to 1.5 per cent., pig-iron of all kinds contains a considerable proportion of carbon. Leaving out of the question irons very high in silicon or manganese, and speaking only of ordinary forge-irons, it

may be said that the carbon runs from 2.3 to 3.8 per cent. It is often supposed that a mottled or white iron will necessarily be low in this element, but such is by no means a certainty, for the close grain may arise from low silicon which is an advantage, from high manganese which is a disadvantage, or from sulphur which is a decided injury.

Low carbon, moreover, is not such an extremely important matter, for although the elimination of this element lengthens the period of the boil, it must be considered that the carbon facilitates fusion, and that its union with the oxygen of the ore reduces metallic iron without forming any objectionable component of the slag.

SEC. 20.—*History of sulphur and phosphorus in the puddling furnace.*—The elements which have thus far been found to be factors in the operation are silicon, manganese and carbon. In the case of reasonably pure irons, like those used in the manufacture of ordinary acid Bessemer and open-hearth steels, these are all that it would be necessary to discuss, for with such irons it would suffice to eliminate these three elements in the presence of any ordinary basic slag, and by balling and working the pasty mass, produce a wrought-iron of good quality. These pure irons, however, are not always obtainable at as low a cost as those containing a greater percentage of phosphorus and sulphur, so that it is necessary to consider the effect of these impurities.

Sulphur.—It was explained in the preceding chapter that the content of sulphur in pig-iron is determined much more by the working of the blast-furnace than by the nature of the ore; but the continual demand for a low-silicon, low-carbon, close-grained iron for the puddler puts the furnaceman between two fires, and the not infrequent result is a pig containing from .10 to .50 per cent. of sulphur. This is materially reduced in the process of puddling by passing away as sulphurous acid in the waste gases and by being carried off in the cinder in combination with iron and manganese.

Phosphorus.—It has also been explained that the content of phosphorus in pig-iron is not determined in any appreciable degree by the furnaceman, for under ordinary conditions almost all that exists in the ore and fuel is found in the product. In the puddle-furnace, on the contrary, this metalloid is under

more or less control, and it may be roughly stated that three-quarters of the total content may be eliminated, this broad formula being profoundly influenced by the skill of the puddler and the purity of the reagents. The presence of phosphorus in the ore used for fettling the hearth must necessarily detract just so much from the purifying power of the slag made from it, while the silica in the ore decreases the basicity of the slag and, therefore, its capacity for absorbing phosphorus; needless to say that silicon in the iron, producing silica by oxidation, acts in the same way. A rough sketch of the chemical history of the puddling process is shown by Table 11, which gives the composition of metal and slag at various stages of the operation.

SEC. 21.—*Effect of the temperature of the furnace upon the puddling process.*—The temperature of the furnace has an important bearing on the character of the product, particularly when much carbon is present. Experiments are cited by Stead* showing that in the refining process, which corresponds to the first part of the puddling process, the elimination of phosphorus was inversely as the temperature, ranging from 46 per cent. in hot charges to 91 per cent. with cold working, in each case about 96 per cent. of the silicon and 30 to 40 per cent. of the carbon being oxidized. For many years the phenomenon was explained by supposing that phosphorus would not unite with oxygen at high temperatures, and this was deemed to be conclusively proven by the fact that phosphorus was not burned in the acid Bessemer converter. It is now known that the reduction of phosphorus by high heat in the puddling-furnace is due to the very simple fact that carbon has a greater affinity for oxygen as the temperature rises, so that it reduces the phosphate of iron and returns the phosphorus to the metal. Thus there is an inversion of the relative attraction of carbon and phosphorus for oxygen rather than a negation of affinities. These facts are now thoroughly understood in the metallurgical world, and, on the one hand, the refinery produces a dephosphorized high-carbon metal by carrying on the oxidation in a cool furnace, while on the other the basic Bessemer eliminates phosphorus at the highest temperatures by the use of irreducible bases.

* *Journal I. and S. I.*, Vol. II, 1877, p. 372.

It is the practice at most works to remove part of the slag while the metal is high in carbon, the product so made being called "boilings," while the slag which is left in the furnace

TABLE 11.

Elimination of the Metalloids in the Puddling Process.

Nature of Sample.	Composition, per cent.											
	Metal.							Slag.				
	Si	Carbon		Mn	P	S	SiO_2	SiO_2	Fe_2O_3	FeO	MnO	P_2O_5
PIG IRON NO. 1,	2.80	3.12		. .	1.47	.11	. . .	. . .	. . .	. . .	. . .	. . .
Refined,	.12	2.50		. .	.84	tr.	. . .	. . .	. . .	. . .	. . .	. . .
Finished bar,	.19	tr.		. .	.27	tr.	. . .	. . .	. . .	. . .	. . .	. . .
PIG IRON NO. 2,	1.236	3.180		. .	1.494	.111	. . .	. . .	. . .	. . .	. . .	. . .
After melting,	.821	2.830		. .	.913	.096	. . .	. . .	. . .	. . .	. . .	. . .
During the boil	.200	2.800		. .	.582	. . .	. . .	. . .	. . .	. . .	. . .	. . .
" " "	.051	1.170		. .	.519	. . .	. . .	. . .	. . .	. . .	. . .	. . .
Finished bar,	.098	.150		. .	.452	. . .	. . .	. . .	. . .	. . .	. . .	. . .
PIG IRON NO. 3,	1.36	3.20		. .	1.39	.17	. . .	. . .	. . .	. . .	. . .	. . .
Refined,	.07	2.00		. .	.32	.06	. . .	. . .	. . .	. . .	. . .	. . .
Forming into grain,	.04	1.90		. .	.20	.02	. . .	. . .	. . .	. . .	. . .	. . .
Dropping on grain,	.04	1.15		. .	.30	tr.	. . .	. . .	. . .	. . .	. . .	. . .
Finished bar,	.07	.05		. .	.33	.04	. . .	. . .	. . .	. . .	. . .	. . .
		Comb.	Graph.									
PIG IRON NO. 4,	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
After melting,	1.11	0.61	1.75	.78	.36	. . .	. . .	24.04	18.74	51.22	4.42	1.30
Bath growing thicker,	.14	1.89	tr.	tr.	.25	. . .	. . .	27.17	5.28	59.56	5.17	2.12
Coming up on boil,	. . .	1.75	. .	.09	.26	. . .	.74	27.77	4.81	59.95	5.29	2.19
Beginning to drop,	. . .	1.57	. .	tr.	.23	. . .	1.01	27.46	4.19	58.41	55.45	2.22
Dropped; infusible,	. . .	1.10	. .	tr.	.23	. . .	1.37	25.72	4.20	60.61	4.65	2.07
Balling,	. . .	.25	. .	tr.	.25	. . .	.91	15.79	9.21	69.52	2.81	1.66
Finished bar,	. . .	.16	. .	.07	.09	. . .	.28	. . .	. . .	. . .	. . .	. . .

NOTE.—The data on pig irons Nos. 1, 2 and 3 are taken from investigations by Beil; see *Journal I. and S. I.*, Vol. I, 1877, pages 120 and 122.

Those on No. 4 are from a paper by Louis. *Journal I. and S. I.*, Vol. I, 1879, p. 222, it being stated that after the fourth test it was impossible to get a fair average owing to the viscosity of the mass, and hence the analyses must be considered only approximately representative.

The abbreviation tr. signifies trace, while comb. and graph. stand for combined and graphitic carbon.

at the end of the operation and which is sometimes tapped from the bottom is called "tappings." This last cinder is often allowed to remain, or, if tapped, is charged with the next heat in order to furnish a rich slag in the early part of the process, since the fettling of iron ore is so infusible that it cannot furnish a cinder until a high temperature is attained. The

removal of the "boilings" during the operation hastens the work, gives less cutting of the bottom, and renders the "balling" easier. It also follows that it aids dephosphorization, for during the first part of the operation the charge is naturally at a low temperature, and the slag, therefore, carries a higher percentage of phosphorus than it would retain if it were kept in the furnace and exposed to a high temperature and the reducing action of carbon. By tapping during the first part of the boil, the greater part of the silica and phosphorus is removed and there is an opportunity to make a new slag richer in iron and of greater dephosphorizing power.

It is the first slag which is generally known as puddle or mill cinder and which is often used in the blast-furnace. It is very variable in composition, as will be evident from Table 12, which gives analyses from various sources indicating the general nature of the material.

Table 12.

Analyses of Puddle or Mill Cinder.

Where Made.	Authority.	Composition, per cent.				
		SiO_2	Fe	P	Mn	S
Harrisburg, Pa.,	Author.	19.91	49.07	1.10	1.27	. . . .
"	"	11.64	60.86	1.07	. . . .	. . . .
"	"	19.58	55.06	1.81	. . . .	0.24
"	"	21.38	56.04	1.41	3.62	. . .
Troy, N. Y.,	*Trans. A. I. M. E.*, Vol. IX, p. 14,	13.81	53.44	1.91	. . . .	. . . .
Ironton, Ohio,	*Trans. A. I. M. E.*, Vol. IX, p. 14,	30.00	50.59	0.54	. . . .	. . . .
Marietta, Ohio,	*Trans. A. I. M. E.*, Vol. IX, p. 14,	21.58	51.42	1.40	. . . .	. . . .
Three English Works, "Boilings,"	*I. and S. I.*, Journal, Vol. I, 1891, p. 119,	19.45	53.55	2.76	. . . .	. . . .
Three English Works, "Tappings,"	*I. and S. I.*, Journal, Vol. 1, 1891, p. 119,	15.47	59.29	1.71	. . . .	. . . .

Sec. 22.—*Effect of work upon the physical characteristics of wrought-iron.*—The influence of the different elements upon the quality of wrought-iron has never been fully discovered owing to the many disturbing conditions, foremost among which is the effect of varying amounts of work upon the finished material. This question arises in the case of steel, but it is much more important in wrought-iron, since the strength of the bar will depend in great measure upon the thoroughness with which the separate pieces forming the

mass have been welded and forced together. With well-constructed piles and sufficient reductions, the tests on thick plates are fully as good as on thin sheets.

In Table 13 are given a few averages of results obtained at the Central Iron and Steel Works at Harrisburg, Pa., from plates rolled on their ordinary three-high train, and from

TABLE 13.

Tests on Wrought-Iron Plates from Shear and Universal Mills of the Central Iron and Steel Works, Harrisburg, Pa.

	Sheared Plates.					Universal Mill Plates.				
Thickness in inches.	Number of tests averaged.	Elastic limit, lbs. per square inch.	Ultimate strength, lbs. per square inch.	Elongation in 8 in., per cent.	Reduction of area, per cent.	Number of tests averaged.	Elastic limit, lbs. per square inch.	Ultimate strength, lbs. per square inch.	Elongation in 8 in., per cent.	Reduction of area, per cent.
$\frac{1}{4}$	1	32400	51800	11.2	18.9	1	32100	51000	13.0	19.9
$\frac{3}{8}$	. . .	. . . . .	. . . . .	. . . .	. . . .	2	31050	50650	14.6	21.6
$\frac{1}{2}$	5	31180	49760	14.2	22.0	3	31100	50530	17.3	26.2
$\frac{5}{8}$	4	30775	50200	15.5	22.5	3	30500	50830	17.2	24.6
$\frac{3}{4}$	2	30400	49050	16.0	22.4	3	31470	52570	19.0	26.2

those made on a 25-inch universal mill. The better figures for the latter mill are due to the more complete development of fibre by the continuous rolling in one direction.

The width was about alike for similar thicknesses, and no difference was found in the universal plates whether they were 9 or 42 inches in width. The above results are too few for a valid comparison, but they are corroborated by the regular practice at this works where the universal plates are superior to the product of the shear mill. In all these cases, the stock from which the iron was made was the same, and the tensile strength is constant for all thicknesses. Moreover, there seems to be a better elongation as the thickness increases, while the reduction of area is fully as high.

With less careful work there is a constant retrogression in quality as the size of the finished piece increases, and this is usually recognized in specifications, as will be seen by Table 14, which is copied from a paper by A. E. Hunt.*

SEC. 23.—*Heterogeneity of wrought-iron.*—The most com-

* *On the Inspection of Materials of Construction in the United States. Journal I. and S. I.*, Vol. II, 1890, p. 299.

plete investigation on the subject of wrought-iron is a report by Holley* on the work of a Board appointed by the United

TABLE 14.

Average Requirements on Wrought-Iron in the United States.

Kind of Material.	Tensile Tests.				Cold Bending Tests.	
	Limit of elasticity, lbs. per square in.	Ultimate strength, lbs. per square in.	Elongation in 8 in., per cent.	Reduction of area, per cent.	Angle of bend.	Diameter of cylinder around which the specimen is to be bent.
BAR IRON.						
Round bars up to 1½ in. diameter,	26000	50000	18	25	180°	Upon itself until sides come in contact.
Round bars up to 2⅜ in. diameter,	26000	50000	15	20	160°	One diameter of bar.
Square bars up to 1½ in. per side,	26000	50000	18	25	180°	Upon itself until sides come in contact.
Square bars of less than 4½ square inches sectional area,	26000	50000	15	20	180°	Diameter equal to the sides of bar.
Flat bars of less than 4½ square inches sectional area,	26000	50000	15	20	180°	Diameter equal to twice the thickness.
Bars of more than 4½ square inches sectional area,	26000	50000	12	18	140°	Two diameters of bar.
CHANNELS AND BEAMS.						
Test from web,	26000	47000	12	18	140°	Diameter equal to thickness of bar.
Test from flange,	26000	49000	15	20	160°	" " " "
Angle iron,	26000	49000	13	20	140°	" " " "
Other shapes,	26000	48000	14	18	120°	" " " "
PLATE IRON; tests to be taken with the fibre.						
Under 18 inches wide,	26000	50000	15	20	160°	Diameter twice the thickness.
18 to 36 inches wide,	26000	48000	12	16	100°	" " " "
36 to 54 inches wide,	25000	46000	10	10	90°	" " " "
Over 54 inches wide,	25000	46000	8	8	90°	" " " "

States Government to test material for chain cables. It was found that the tenacity of 2-inch bars for chain cables should

* *The Strength of Wrought-Iron as Affected by its Composition and by its Reduction in Rolling. Trans. A. I. M. E.,* Vol. VI, p. 101.

be from 48000 to 52000 pounds per square inch, while 1-incn bars should show from 53000 to 57000 pounds. This conclusion is reached after very careful reasoning, and it illustrates the profound influence of this one item of reduction in rolling. It will be evident that unless the history of the bar is known, ordinary chemical analysis will fail to give any information as to whether it has been rolled from a pile 4 inches square or from one 7 inches square. In the making of rounds, which was the only shape tested by the Board, there is opportunity for very bad practice in beginning to form the piece too early in the operation, for there is a much better chance to work and weld the iron in closed rectangular passes than in the formation of round sections. Usually, a bar which has not received sufficient work will contain an abnormal percentage of slag, and this can be determined in the laboratory; but a slight excess does not necessarily imply that the iron has not been well worked, for it may arise from viscosity of the cinder, rendering its expulsion difficult. In any event, it will be seen that, although a certain quantity may benefit the metal by preventing crystallization, anything beyond this must decrease the cohesion of the particles of iron.

In the investigation just mentioned, it was found that the slag varied from 0.192 per cent. to 2.262 per cent. of the total weight of the iron; and it must be remembered that these tests were made on material destined for a service calling for the best product of the mill. Some makers may have supposed that the presence of slag would facilitate welding, but the investigation did not bear this out, for it is distinctly stated in the report that, while "slag should theoretically improve welding, like any flux, its effect in these experiments could not be definitely traced." On the contrary, the iron which was highest in slag (2.26 per cent.) "welded less soundly than any other bar of the same iron, and below average as compared with the other irons."

The percentage of slag not only varied in different brands of iron but in pieces of the same make. This was true also of all the factors investigated. Table 15 shows the variations in the same make of iron, two extreme cases being given under each head. It also gives the maximum and minimum individual records.

SEC. 24.—*Conditions affecting the welding properties of wrought-iron.*—These conditions of varying work, percentages of slag, and irregularity of the same irons, not to mention the possible overheating of piles in the laudable effort to produce a perfect weld, complicate so fundamentally the relation between the chemical composition and the physical properties, that it need not be wondered that the committee could not find the exact influence of each chemical component.

TABLE 15.

Variations in the Character of Different Specimens of the Same Brands of Wrought-Iron and of Different Irons as Submitted to the United States Board for Testing Chain Cables.

Subject.	Same Iron.		All Irons.	
	Min.	Max.	Min.	Max.
Carbon, per cent.,	.026 .042	.064 .512	.015	.512
Phosphorus, per cent.,	.065 .095	.232 .250	.065	.317
Silicon, per cent.,	.028 .182	.182 .321	.028	.321
Manganese, per cent.,	tr. .021	.059 .097	tr.	.097
Slag, per cent.,	0.674 1.248	1.738 2.262	0.192	2.262
Ultimate strength, pounds per square inch,	56201 47478	69779 57367	47478	69779
Elongation in 8 inches, per cent.,	11.7 14.1	20.6 32.5	6.5	32.7
Reduction of area, per cent.,	27.7 16.0	59.8 31.5	7.7	59.8

There was formulated, however, the following very valuable conclusion: "Although most of the irons under consideration are much alike in composition, the hardening effects of phosphorus and silicon can be traced, and that of carbon is obvious. Phosphorus up to .20 per cent. does not harm and probably improves irons containing silicon not above .15 per cent. and carbon not above .03 per cent. None of the ingredients, except carbon in the proportions present, seem to very notably affect the welding by ordinary methods."

Regarding this last clause it should be said that the highest sulphur in any sample was .015 per cent., which is very low; but that copper was present in one instance up to .43 per

cent.; nickel up to .34 per cent., and cobalt up to .11 per cent. Moreover, the high percentages of these three elements were coincident in one bar, yet welding gave fair results, notwithstanding that phosphorus was higher than was found advisable. A careful reading of the evidence, however, indicates that the experiments were far from conclusive as to these elements.

This matter of welding power was of vital moment in iron for chain cables, but it is also the very root of the entire process, for the integrity of the finished bar depends upon the completeness of the welds between the different particles. In Chapter XIX the welding of iron and steel will be discussed at greater length.

CHAPTER IV.

STEEL.

SECTION 25.—*Definition of steel.*—Although it seems a perfectly simple matter to give a definition of steel, the task has never yet been accomplished to the satisfaction of all concerned. A true formula must apply not only to all the metals commonly designated by the term, but to all compounds which ever have been, or ever will be, worthy of the name, including the special alloys made by the use of chromium, tungsten, nickel and other elements introduced to give peculiar qualities for special purposes.

Prior to the development of the Bessemer and open-hearth processes there was little room for disagreement as to the dividing line between steel and iron. If it would harden in water, it was steel; if not, it was wrought-iron. When the modern methods were introduced, a new metal came into the world. In its composition and in its physical qualities it was exactly like many steels of commerce, and naturally and rightly it was called steel. By degrees these processes widened their field, and began to make a soft metal which possessed many of the characteristics of ordinary wrought-iron, and which was not made by any radical change in methods, but simply by the use of a rich ferromanganese. Notwithstanding this fact, some engineers claimed that the new metal was not steel, but iron. The makers replied that it was made by the same process as the hard steel, and that it was impossible to draw a line in the series of possible and actual grades of product which they made.

The problem rapidly became of great importance, since the filling of engineering contracts and the interpretation of tariff schedules depended upon the application of the one term or the other to the soft product of the converter and the melting-

furnace. At this juncture an international committee was appointed from the leading metallurgical societies of the world, and a list of the members shows us a formidable array of well-known names: Holley, Bell, Wedding, Tunner, Akerman, Egleston and Gruner.

This committee reported in October, 1876, to the American Institute of Mining Engineers, the following resolution:

(1) That all malleable compounds of iron with its ordinary ingredients, which are aggregated from pasty masses, or from piles, or from any forms of iron not in a fluid state, and which will not sensibly harden and temper, and which generally resemble what is called "wrought-iron," shall be called *weld-iron.*

(2) That such compounds, when they will from any cause harden and temper, and which resemble what is now called "puddled steel," shall be called *weld steel.*

(3) That all compounds of iron with its ordinary ingredients which have been cast from a fluid state into malleable masses, and which will not sensibly harden by being quenched in water while at a red heat, shall be called *ingot iron.*

(4) That all such compounds, when they will from any cause so harden, shall be called *ingot steel.*

The Institute, in accordance with its rules, declined to promulgate any official opinion on the subject, but did recommend that the proposed nomenclature be used in all future papers presented at its meetings.

SEC. 26.—*Decadence of the German nomenclature.*—It is fortunate that no more positive action was taken in forcing into use a system which was radically wrong. This classification disregarded a primal necessity of business, for it is necessary to have a name for the material while in process of manufacture. As a practical maker of a certain material used in the arts, I wish a title by which to call it. I can not give orders to make a heat of ———— and wait until it is made, rolled, chilled in water, and tested for hardness before it can have a generic name. The word "steel" was in use for this very purpose in every Bessemer and open-hearth plant in the country; and when the name was once given at the converter or the furnace, it clung throughout its history in the rolling mills and shops.

Had this circle of scientists never met, the engineering world would soon have learned that all the metals made by the Bessemer and open-hearth processes were varieties of steel, and this nomenclature would have become as universal among engineers in our country as it is among manufacturers. This well-intentioned interference spread broadcast an objectionable and impossible classification, but the harm was gradually passing away as the work of the committee was forgotten, when Mr. Howe, in his "Metallurgy of Steel," revived the discarded conceit.

His attempt, however, is recognized as hopeless even by himself, for he opens his great work, published fourteen years after the committee had issued its manifesto, by saying this:* "The terms Iron and Steel are employed so ambiguously and inconsistently that it is to-day impossible to arrange all varieties under a simple and consistent classification." And he adds, with some triumph in the memory of forensic victories, but more pathos over the record of disappointed hopes, that the result would have been quite different "could the little band, which stoutly opposed the introduction of the present anomaly and confusion into our nomenclature, have resisted the momentum of an incipient custom as successfully as they silenced the arguments of their opponents." He closes by completely surrendering to the enemy in these words: "So firmly has this (generic) sense of the word become established that, unfortunately, it were vain to oppose it."

It is a pity that after this acknowledgment of the final judgment of the metallurgical world, he should commend the practice of calling malleable-iron castings by the name of steel,† simply because they coincide with a definition he has just branded as obsolete, for in so doing he sanctions what is to-day one of the greatest frauds in the business. Steel castings are made by pouring melted steel into a flask. This steel must be made either in a crucible, an open-hearth furnace, or a Bessemer converter, for it is impossible to melt scrap in a cupola and have good steel run from the taphole. It is either ignorance or crime to call by the name of steel castings the hybrid metal made by melting a mixture of pig-

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* *Metallurgy of Steel*, p. 1.

† *Loc. cit.*

iron and steel scrap in a cupola, and it just as far from truth to apply the term to malleable iron. Any definition of steel which gives room for these mistakes writes its own epitaph as erroneous and absurd.

SEC. 27.—*Cause of failure of certain proposed definitions.*—One reason has already been given why the projected renaissance of a decayed nomenclature was a failure. But although the lack of any other general term to denote the product of the converter was a most formidable obstacle, it is easy to believe that this could have been overcome. The whole structure, however, lacked a foundation, because there can be no satisfactory definition as to what constitutes *hardening*. It will not do to prescribe any test with a file, for there is too much chance for personal equation in such a trial, not to mention the impossibility of having every file of exactly the same hardness. It will not do to make a quench bend, for the success of such a test is determined in too great a measure by certain variable conditions of the preheating not fully understood, and by the manipulations of the smith.

All these points were fully understood by practical men at the time the committee was at work, and the arguments were ably presented by Park and Metcalf.* They asked for a definition as to what constituted hardening, and received the answer that a dividing line is unnecessary. Prof. Akerman† recommends that it be placed where the quenched piece can not be scratched by feldspar. He recognizes that small variations in many elements other than carbon will determine the amount of hardening, and also mentions the difference caused by the temperature of the water and the way in which the piece is immersed, and whether it is held still or moved. If the learned professor had wished to condemn his case, he could have done little more. Laboratory experiments on quenching and scratching with feldspar are well enough for some purposes, but when these must be performed before the material can have a name, and when such work gives us

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* *Can the Commercial Nomenclature of Iron be Reconciled to the Scientific Terms Used to Distinguish the Different Classes?* Metcalf; *Trans. A. I. M. E.*, Vol. V, p. 355.

† *On Hardening Iron and Steel; Its Causes and Effects. Journal I. and S. I.*, Vol. II, 1879, p. 512.

simply the name and no other information at all, then, surely, the matter presents itself in the form of a *reductio ad absurdum.*

It is true, as argued by Mr. Howe, that many of the common products of metallurgy and art shade imperceptibly into one another; but it is surely extraordinary when the dividing line cannot be drawn even in theory, much less in practice; when, wherever it falls, it must divide, not intermediate, but finished products, used in enormous quantities, and blending into one another by insensible gradations, and when every shade of these variations is the subject of rigorous engineering specifications.

It is customary and necessary in ordering steel to give a certain margin in filling the specifications, and it will be evident, no matter how close this margin is, that if a line could be drawn, it would not infrequently happen that he who ordered ingot iron would receive steel, and he who ordered steel would receive ingot iron.

SEC. 28.—*Difficulty of writing a definition of hardening.*—Many different tests have been proposed at various times for determining the mechanical properties of steels, but although some of them are of value in special cases, the one method of investigation which has become well-nigh universal is to break by a tensile stress and measure the ultimate strength, the elastic limit, the elongation, and the reduction of area. Strictly speaking, none of these properties has any direct connection with hardness, and it is also true that in special instances, as with very high carbons, hardening may reduce the tensile strength by the creation of abnormal internal strains; but in all ordinary steels, it is certain that hardening is accompanied by an increase of strength, by an exaltation of the elastic limit, and a decrease in ductility.

Now, if it is conceded that no practical test defining hardening has ever been devised, and if it can be shown that sudden cooling produces a very marked increase in ultimate strength, an exaltation of the elastic limit, and a decrease in ductility even in the softest products of the converter and the open-hearth furnace, then we are partially justified in assuming that hardening has occurred on the ground that the more easily recognized correlated phenomena continue in

unbroken order down the scale of the various iron products. The conclusion is weak in logic, I will admit, but from the standpoint of the engineer of to-day, who grades everything by the tensile test, and who makes "strong" steel and "hard" steel interchangeable terms, I claim good ground for my position in calling steel hardened when it is strengthened.

SEC. 29.—*Effect of quenching soft steel.*—The fact that common soft steel is materially strengthened by chilling has been widely recognized for many years, but the extent of the alteration in physical properties in the softest and purest metals is not generally understood. Table 16 gives a series of tests that I have made, which may shed some light on this point.

TABLE 16.

Effect of Quenching on the Physical Properties of Different Soft Steels.

NOTE.—Bars were 2″x⅜″ flats, rolled from a 6″x6″ ingot, and were chilled at a dull yellow heat.

Number of test-bar.		1	2	3	4	5	6
Composition, per cent.	Carbon,	.09	.12	.11	.12	.09	.10
	Manganese,	.44	.32	.43	.32	.39	.16
	Phosphorus,	.011	.004	.010	.004	.017	.010
	Sulphur,	.033	.027	.010	.027	.031	.019
Ultimate strength; pounds per sq. inch,	Natural,	49390	48960	48960	48260	49760	46250
	Quenched,	66080	65670	66300	63640	62280	58380
Elastic limit; pounds per square inch.	Natural,	33220	33390	33010	32340	31040	29830
	Quenched,	47310	und.	und.	50170	46580	40500
Elastic ratio, per cent.	Natural,	67.26	68.20	67.42	67.01	62.38	64.50
	Quenched,	71.60	und.	und.	78.83	74.79	69.38
Elongation in 8 in.; per cent.	Natural,	29.75	31.00	32.50	32.50	31.25	37.75
	Quenched,	18.75	16.25	15.00	17.75	23.75	27.50
Reduction of area; per cent.	Natural,	50.80	52.50	54.10	55.75	49.00	68.38
	Quenched,	56.50	63.27	63.47	64.47	65.15	68.97

As the bars were rolled from a small test ingot, the elongation is much less than the normal, but the consequences of the quenching are well marked. Additional tests were made on another sample of soft basic open-hearth metal. The original piece was a rolled flat, 4 inches wide and 5-16 inch thick. This was cut lengthwise into two strips, 1¾ inches wide by 5-16 inch thick, and these strips were again cut into 18-inch lengths, so that the whole bar gave 12 test-pieces. Six of these were taken from alternate sides of the original bar throughout its length and tested without treatment, while the other six were broken after chilling at different temperatures. The results are given in Table 17.

There is possibly a mixture of tests in the case of the "dark cherry red" and "medium cherry red," or perhaps an error in estimating temperature, but I give the results as they were recorded. The elongation is not given, for the pieces persisted in breaking near the grips. This may have arisen from the fact that the ends of the bars as they lay in the muffle were not as hot as the middle, and hence did not receive so severe a chilling, but the difference is not enough to invalidate the

TABLE 17.

Effect of Quenching the Same Steel at Different Temperatures.

Bars $1\frac{3}{4}'' \times \frac{5}{16}''$; Composition, per cent.; C (by combustion) .057; Mn .33; P. 006; S .019.

Heat treatment.	Ultimate strength; pounds per square inch	Elastic limit; pounds per square inch	Elongation in 8 inches; per cent.	Reduction of area; per cent.	Elastic ratio; per cent.
Natural state; average of 6 bars . .	46098	33825	35.37	70.00	73.37
Chilled at a dull red heat	49740	33800	Broke near jaws.	70.00	67.95
" " dark cherry red	56500	38830		63.80	68.73
" " medium cherry red . .	51100	34570		70.30	67.65
" " cherry red	57240	39060		66.10	68.24
" " low bright red	58200	39930		64.80	68.61
" " bright red	62640	38860		63.10	62.04

nature of the results. The reduction of area is lessened somewhat, but this seems to be affected much less by chilling than the other properties, a fact which is also shown in Table 16.

The untreated bars show that the metal was of extreme softness, while the chilled specimens prove that each change in the quenching temperature is reflected in the physical condition of the chilled bar.

SEC. 30.—*The American nomenclature of iron products.*—The classification by hardening is a dead issue in our country. It had quietly passed away unnoticed and unknown before the Committee of the Mining Engineers had met, and the best efforts of that brilliant galaxy of talent could only pronounce a kindly eulogy.

Strictly speaking, some mention must be made of hardening in a complete and perfect definition, for it is possible to make steel in a puddling furnace by taking out the viscous mass before it has been completely decarburized; but this crude and unusual method is now a relic of the past, and may be

entirely neglected in practical discussion. No attempt will be made here to give an ironclad formula, but the following statements portray the current usage in our country.

(1) By the term wrought-iron is meant the product of the puddle furnace or the sinking fire.

(2) By the term steel is meant the product of the cementation process, or the malleable compounds of iron made in the crucible, the converter, or the open-hearth furnace.

This nomenclature is not founded on the resolutions of committees or of societies. It is the natural outgrowth of business and of fact, and has been made mandatory by the highest of all statutes—the law of common sense. It is the universal system among engineers not only in America, but in England and in France. In other lands the authority of famous names, backed by conservatism and governmental prerogative, has fixed for the present, in metallurgical literature, a list of terms which I have tried to show is not only deficient, but fundamentally false.

CHAPTER V.

HIGH-CARBON STEEL.

SECTION 31.—*Manufacture of cement and crucible steel.*—By the use of reasonably pure ores and by skillful puddling, it is quite possible to produce wrought-iron in which the phosphorus shall not exceed .02 per cent. This bar of soft pure iron may be converted into hard steel by placing it in fine charcoal and exposing it to a yellow heat. By a slow process, called cementation, the carbon penetrates the metal at the rate of about one-eighth inch every 24 hours, so that a bar five-eighths of an inch thick is saturated about 48 hours after it arrives at a proper temperature. This operation is carried on in a large retort where many tons of bars are treated at one time, so that it will always happen that some parts of the furnace arrive at a full heat much sooner than others, and remain longer at that temperature. Consequently, when such a retort is opened, it is necessary to break all the bars and grade them by fracture according to their degree of carburization. The point of saturation is about 1.50 per cent. of carbon, but the average of the whole will be about one per cent.

The steel thus produced is known as blister or cement steel. Its use is limited by the fact that it always contains seams and pits of slag which were present in the wrought-iron, and these defects are of fatal moment in the manufacture of edged tools. To avoid this trouble, cement steel may be melted in crucibles, out of contact with the air, and, being thus freed from the intermingled slag, can be cast into ingots and hammered or rolled into any desired shape. This double process is expensive, and a cheaper and more common method is to put a proper quantity of charcoal into the crucible with crude bar iron, the absorption of carbon progressing with great rapidity when the metal is fluid. This practice is almost

universal in America, and it is claimed by men whose word must carry weight in the metallurgical world, that it gives a steel equal in every respect to the older method; but against this must be put the work of firms whose name is synonymous with most excellent product and who, at much extra cost, use a certain proportion of cemented bar for the most expensive steels. It is difficult to say how much of the extra quality is due to the method of manufacture and how much to the strictest care in working and inspecting, and it is also hard to find out whether the conservatism does not arise from the laudable desire to supply old customers with exactly the same metal, in name as well as in fact, that has been furnished them in the past.

In deference to time-honored tradition, it may be well to quote without approval or further dispute the following dictum of Seebohm,* which expresses the ancient doctrines: "The best razor steel must be melted from evenly converted steel. It will not do to mix hard and soft steel together, or to melt it from pig 'let down' with iron, for it will not then possess the requisite amount of body and the edge of the razor will not stand."

A third variation is the melting of wrought-iron with a proper proportion of pig to raise the carbon to the desired point, while in still another, used in Sweden, the charge of the crucible consists of pig and iron-ore. The aim of all methods is to obtain a malleable metal containing from .60 to 1.40 per cent. carbon, and free from blowholes. For certain purposes some special element like chromium, or tungsten, may be used as an alloy, but with this exception every other ingredient may be regarded as an impurity.

SEC. 32.—*Chemical reactions in the steel-melting crucible.*—The best tool steel must be as tough as possible, and, therefore, the phosphorus should not be over .02 per cent. Sulphur, which does not appreciably affect brittleness, but which does decrease forgeability, is not quite so important, but should not exceed .04 per cent. Manganese may be present in larger quantity, and it is not an uncommon practice to put into the pot a mixture of manganese ore and carbon so that metal-

* *On the Manufacture of Crucible Cast-Steel. Journal I. and S. I.*, Vol. II, 1884, p. 372.

lic manganese may be reduced and confer better forging qualities. If the percentage does not exceed .20 it has very little bad effect; if much above this, it will cause brittleness and liability to crack in quenching.

As in every branch of industry, a simple outline of operations such as is given above may be elaborated indefinitely by the description of the variations in practice which have been developed in different works. Some such details seem absolutely essential to the originators, but they may be unknown at other equally successful establishments.

There is one feature, however, known as "killing," which is in universal use. Just after the steel is melted there is more or less action in the crucible, since there are several rearrangements to be consummated. Thus, in addition to the iron and charcoal in the pot, there is a small amount of glass or similar material to give a passive slag; there is also a little air, some slag and oxide of iron in the puddled bar, the scale and rust on the surface of each piece of metal, and silica, alumina and carbon from the scorification of the walls. A little time is necessary after fusion for the various reactions to occur between these factors and for the attainment of chemical equilibrium. Aside from these general reactions, the special work of the "killing" epoch is the reduction of silicon from the slag and lining in accordance with the following equation:

$$SiO_2 + 2C = Si + 2CO.$$

The carbon is drawn either from the charcoal, from the metal, or from the walls of the crucible. In the case of graphite pots the supply from the latter source will be more than ample, while even clay pots furnish quite an amount from the coke which is mixed with the clay in their manufacture. This process of reduction goes on until the steel contains from .20 to .40 per cent. of silicon and the metal lies quiet and "dead." The pot is then taken from the furnace by means of tongs, and the contents are cast into ingot form. The crucible lasts from four to six heats, and the weight of a melt is about 80 pounds when the crucible is new, the subsequent charges being regulated according to the strength of the scorified walls, and by the desire to lower the level of the slag line to the less affected portions.

SEC. 33.—*Chemical specifications on high steel.*—In olden times all springs, tools, dies, and the like, were made from either cement or crucible steel, but in late years large quantities of high-carbon metal have been produced in the Bessemer converter and used for many common purposes, although, ordinarily, the steel made by this process contains too much phosphorus to make it suitable for the best work. The manganese in Bessemer steel is much higher than in crucible metal, and this has a tendency to cause cracks in quenching. Formerly a content of .75 to 1.10 per cent. was not uncommon, but the demands of the trade have forced an improvement in this respect, and it is now customary to keep the manganese below .80 per cent.; it is impracticable to have it much below .50 per cent. on account of red-shortness.

It is possible to make a much better selection of the stock for an open-hearth furnace and to produce a steel which is low in manganese, phosphorus, and sulphur. The relative merits of open-hearth and crucible steel have been the subject of vigorous discussions, but, as in many similar cases, the critics who are loudest in expressing their opinions are the least competent to judge. Oftentimes a comparison is made between a pure crucible steel and an open-hearth metal containing about .07 per cent. of phosphorus and .60 per cent. of manganese, and on the strength of this comparison, and taking the word of some ignorant or untruthful open-hearth maker as to the quality of his product, the conclusion is formulated that crucible steel is undeniably superior. Such generalizations on insufficient evidence constitute the large majority of those made in our tool shops, but it is evident that no comparison is valid unless the steels are of the same composition, and in this latter respect it will not do to accept the unproven statements even of makers who rank as virtuous. To show that this last clause is not meaningless, Table 18 gives analyses of three grades of steel, furnished by one of the large and well-known steel manufacturers of the country. The first column shows the name by which the maker billed it.

Needless to say that the carbon content in these metals is right, for otherwise they would be entirely unsuitable, but each sample shows discrepancies between actual composition and name. Crucible steel may and often does contain as

much as .04 per cent. of phosphorus, but no purchaser expects to have that amount when he buys the product of the pot, and when this figure is considered in connection with the high manganese, and above all with the absence of silicon, the

TABLE 18.

Examples of Commercial High Steels which are not in Accordance with Specifications.

Nature of sample as marked by maker.	Composition; per cent.				
	C	P	Mn	Si	S
"Crucible"	1.00	.04	.33	.02	.025
"Pennsylvania Railroad spring" .	.94	.065	.56	.23	.125
"Low phosphorus spring"	.80	.072	.64	.19	.155

natural conclusion is that the metal ran from the taphole of an open-hearth furnace. The second sample is supposed to fill the Pennsylvania Railroad specifications for springs which call for phosphorus below .05 per cent., manganese below .50 per cent., and sulphur below .05 per cent., but a glance will show the liberties that have been taken. The "low phosphorus" spring steel contains .072 per cent. of that element, an amount slightly under the average of common rails, but which can by no stretch of words be called "low" for hard metal. The sulphur is extraordinarily high, but where there are no specifications on this element, there is not much ground for criticism, since it has little influence on the cold properties.

SEC. 34.—*Manufacture of high steel in an open-hearth furnace.*—It is perfectly possible to make regularly, in open-hearth furnaces, a steel of any carbon desired from .05 to 1.50 per cent., with phosphorus below .04 per cent., with manganese below .50 per cent., and with sulphur below .04 per cent. Such steel has not been tried extensively, and the future must decide just how far it will replace the product of the crucible. There are one or two minor points about this material which should be recognized by maker and user. First, there is not as good an opportunity to get a "dead melt" in the furnace as in the pot, and hence there is more liability of blowholes in the ingots, and seams in the bar. For the making of razors, watch springs, and other delicate instruments, no expense is

too great in the avoiding of minute defects, but when these imperfections are few and not of such vital importance, there must inevitably be a tendency to economize in the cost of the raw material.

Second, a heavy heat of open-hearth steel must be cast in masses which are very large in comparison with the 4-inch ingot of the crucible works, and the chances for segregation are correspondingly increased. Table 19 will indicate just how much this danger is to be feared.

The variations in phosphorus, sulphur, manganese, and copper are trifling, while those of silicon are unimportant. In carbon the difference between extremes is 16 points, and while this may seem to be a great variation in one charge, it is necessary to consider that the true comparison is not

TABLE 19.

Composition of Clippings taken from the Top* and Bottom Blooms of Each Ingot of a High Carbon Open-Hearth Heat, Made by the Pennsylvania Steel Company.

Number of Ingot.	Part of Ingot.	Composition; per cent.					
		Carbon by Combustion.	P	Mn	S	Si	Cu
1	Top	1.009	.030	.30	.027	.14	.10
	Bottom	1.080	.031	.29	.026	.13	.10
2	Top	1.046	.029	.29	.027	.15	.10
	Bottom	1.006	.026	.29	.027	.13	.10
3	Top	1.042	.031	.29	.028	.11	.10
	Bottom	0.933	.030	.30	.029	.14	.10
4	Top	1.090	.032	.28	.028	.09	.10
	Bottom	1.027	.034	.29	.025	.12	.10
5	Top	0.948	.035	.32	.026	.17	.10
	Bottom	1.089	.036	.29	.027	.10	.10
6	Top	1.065	.030	.28	.026	.11	.10
	Bottom	1.086	.033	.29	.026	.11	.10
7	Top	1.073	.030	.29	.025	.11	.09
	Bottom	1.043	.028	.30	.028	.15	.10
8	Top	0.982	.029	.30	.025	.12	.10
	Bottom	0.953	.032	.29	.026	.13	.08
9	Top	1.044	.031	.29	.026	.11	.09
	Bottom	0.915	.032	.28	.027	.13	.01
Test.		1.073	.030	.28	.033	.12	.07

*The piece from the upper bloom was from a point corresponding to one-quarter way from the top of the ingot, and was therefore near the point of maximum segregation. The sample was the usual clipping produced in cutting a billet under the hammer.

between one small ingot of crucible steel and a heat of open-hearth metal, but between equal amounts of each. In other words, the question must be asked, whether the irregularities are greater in a lot of ten tons of crucible steel than in ten tons of open-hearth. This cannot be satisfactorily answered, since so much depends upon the care with which the stock is selected, but Table 20 gives some analyses of different bars of one lot of crucible steel, sold under one mark and of uniform size by one of the leading firms in the United States; it will be evident that uniformity can by no means be assumed.

TABLE 20.

Variations in Composition between Different Bars of one Lot of Crucible Steel Rounds.

No. of Bar	Composition, per cent.			
	Carbon by color.	P	Mn	S
1	.85	.013	.20	018
2	.85	.011	.20	014
3	1.05	.010	.17	010
4	.98	.013	.21	.012
5	.90	n.d.	.28	.010

CHAPTER VI.

THE ACID-BESSEMER PROCESS.

SECTION 35.—*Construction of a Bessemer converter.*—The acid-Bessemer process consists in blowing air into liquid pig-iron for the purpose of burning most of the silicon, manganese, and carbon of the metal, the operation being conducted in an acid-lined vessel, and in such a manner that the product is entirely fluid.

The way in which the air is introduced is a matter of little importance as far as the character of the product is concerned. In the earlier days there were many experimental forms of apparatus, the air being blown sometimes from the side and sometimes from the top, while the tuyeres were plunged beneath the surface or raised entirely above it. All these forms have given way to the method of blowing the air upward through the metal, trusting to the pressure of the blast to keep the liquid from running into the holes in the bottom. Within the last ten years a little excitement was raised by a revival of small converters using top or side blast, like the so-called "Clapp-Griffiths" and "Roberts" processes, but as every well-posted metallurgist expected, these projects died in early youth, like their numerous predecessors.

The converters vary widely in size according to the desired output of the plant, in exceptional cases holding less than one thousand pounds, but the common size for what are known as "small" plants treats five tons at a time, while in the "large" plants the capacity is from ten to twenty tons. In Figures II and III are given drawings showing the 18-ton vessels in use at the works of the Maryland Steel Company, at Sparrow's Point, Md.

It is the almost universal practice to rotate the converters on a central axis by means of an hydraulic rack and pinion,

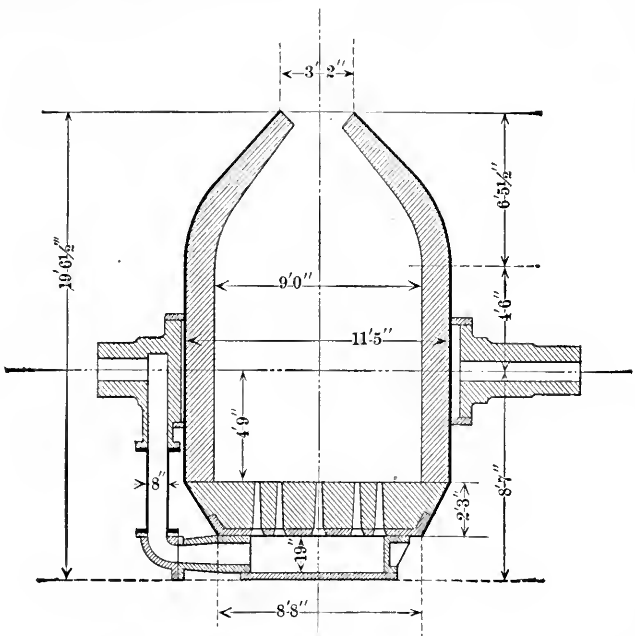

FIG. I.—SECTION OF BESSEMER CONVERTER IN UPRIGHT POSITION.

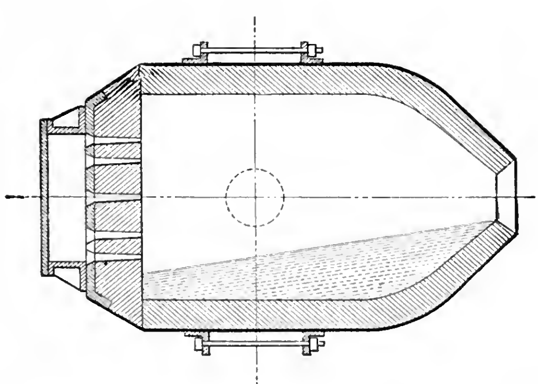

FIG. III.—SECTION OF BESSEMER CONVERTER WHEN TURNED DOWN, SHOWING BATH OF METAL.

in order to allow the turning down of the vessel as soon as the charge is decarburized, so that the metal may lie quietly in the belly, the tuyeres being above the metal, as shown in Fig. III. It is in this way only that a blast from the bottom can be suddenly stopped without filling the tuyeres and air box with molten metal. If bottom blast be used with a stationary vessel, the blast must be continued during all the time required to open the taphole and drain out the metal, so that under the best of practice the results will be more irregular than with a rotary form. This fault may be partly overcome by having the blast introduced from the upper surface, but experience shows that the waste of iron is greater, and this extra expense completely wipes away all advantages of a reduced cost of installation.

The lining is made of stone, brick, or other refractory material, and is about one foot thick. The bottom is made either of brick or rammed plastic material, the tuyeres being almost invariably of brick, from 20 to 26 inches in length, and with holes from three-eighths to one-half inch in diameter. The total tuyere area varies at different works from 2.5 to 4.0 square inches per ton of charge. The blast is kept at a pressure of from 25 to 30 pounds per square inch during the first part of the blow, but in the case of a very hot charge, or if the slag is sloppy, the pressure must sometimes be reduced to 10 pounds after the flame "breaks through" (*i. e.*, after the carbon begins to burn), to prevent the expulsion of metal from the nose. The blowing engine and the tuyere openings being proportionate to the work in hand, the heats, whether heavy or light, are usually blown in from 7 to 12 minutes.

SEC. 36.—*Chemical history of an acid Bessemer charge.*—The chemical history of a typical charge was investigated by F. Julian at the South Chicago Works of the Illinois Steel Company, and his results are given in Table 21, which is copied from a most admirable paper by H. M. Howe.*

The weight of the slag is not recorded, but apparently all the data are given that are necessary to calculate the complete history, for the amount of manganese that burns is

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* *Notes on the Bessemer Process. Journal I. and S. I.*, Vol. II, 1890, p. 102.

known, and, from the percentage which this forms of the total cinder, the deduction may be made that the slag at the end of the fourth period weighs 1385 pounds. This figure seems quite probable, and, with it as a basis, it seems possible to calculate the conditions at earlier stages of the blow. One method of doing this is founded on the content of lime and magnesia. The presence of both of these factors must arise from the introduction of small quantities of cupola or blast-furnace slag into the converter, and, since there is no possible source of supply of either during the process of blowing, they must be in constant quantity throughout the operation. Another method is founded on the content of

TABLE 21.

Chemical History of an Acid-Bessemer Charge.

Illinois Steel Company, South Chicago, Ill., August 13, 1890, F. Julian.

Barometer, 29.79 inches; temperature, 36°C. (96.8° F.); blast pressure, 27 pounds to the square inch. In calculations on volume of air, no allowance is made for leakage or clearance. Weight of pig and scrap, 22,500 pounds. Weight of spiegel, 2500 pounds.

Subject.	Initial Charge.	Time of Blowing.					
		2m. 0s.	3m. 20s.	6m. 3s.	8m. 8s.	9m. 10s.	After Spiegel.
Carbon	2.98	2.94	2 71	1.72	0 53	0.04	0.45
Silicon	0.94	0.63	0 33	0.03	0.03	0.02	0.028
Manganese	0.43	0.09	0 04	0.03	0.01	0.01	1.15
Phosphorus	.10	0.104	0.106	0.106	0.107	0.108	0.109
Sulphur	.06	0.06	0.06	0.06	0 06	0.06	0.059
Silica	. . .	42.40	50.26	62.54	63 56	. . . . .	62.20
Alumina	. . .	5.63	5.13	4.06	3.01	. . . . .	2.76
Ferrous oxide	. . .	40 29	34.24	21.26	21 39	. . . . .	17.44
Ferric oxide	. . .	4.51	0.96	1.93	2 63	. . . . .	2.90
Manganese oxide	. . .	6.54	7.90	8.79	8 88	. . . . .	13 72
Lime	. . .	1.22	0.91	0.88	0.90	. . . . .	0.87
Magnesia	. . .	0.36	0 34	0.34	0.36	. . . . .	0 29
Phosphorus	. . .	0.008	0 008	0.010	0.014	. . . . .	0.010
Sulphur	. . .	0.009	0.009	0 014	0.008	. . . . .	0.011
Flame	. . .	Silicon flame.	bright-ening.	m'der'te carbon flame.	full carbon flame.	flame drops.	. . . . .
Cubic feet of air	. . .	34502	30628	53481	45365	26430	. . . . .

alumina, but this determination would be less reliable, for there is a certain constant increase in the quantity present, owing to the scorification of the bottom. In the present case the calculation has been made by two different hypotheses; first, that no alumina is added to the slag during the blow; second, that 15 pounds enters the cinder between the beginning and end of the operation. A third method is founded on the quantity of manganese in the slag; this amount is changing continually, but as none can enter the slag save from the

iron, and as the composition of the metal is given for each stage of the process, it would seem that reasonably accurate results might be obtained from this source. Table 22 shows the figures thus determined.

A consideration of these figures will show that there are radical errors in the data, since the results do not agree among themselves; in the second calculation, on the basis of MgO, and in the fifth, on the basis of MnO, the work is palpably wrong, since the figured weight of the first slag is greater than that of the final. Without doubt, some of the trouble arises from the incorporation of slag which was left sticking to the sides of the converter from previous heats, and which melted gradually as the blow progressed. There is also great difficulty in procuring a true sample of slag at any intermediate

TABLE 22.

Calculations on Weights of Bessemer Slags. (See Table 21.)

Method of Calculation.	Weight of Slag in pounds.			
	After blowing 2m. 0s.	After blowing 3m. 20s.	After blowing 6m. 3s.	After blowing 8m. 8s.
From content of CaO	1024	1374	1420	1385
From content of MgO	1389	1471	1471	1385
From content of Al_2O_3; no increase assumed	746	819	1034	1385
From content of Al_2O_3; 15 pounds increase assumed	480	624	911	1385
From content of MnO	1514	1443	1331	1385

stage of the operation owing to its viscous nature. These conditions, coupled with a certain error caused by the slopping of slag from the converter, render it impossible to write the chemical history from the data of one charge. The above attempt is recorded to show the limits which bound any such series of analyses.

Similar discrepancies will be found between the amount of oxygen theoretically necessary to burn the metalloids, and the quantity actually supplied. Up to the fifth test the oxygen needed for the combustion of the silicon, manganese, and carbon (to CO) should be 1148 pounds. To this must be added about 67 pounds which is absorbed by the iron in the slag, giving a total of 1215 pounds. The volume of air actually supplied was 190,406 cubic feet, containing 2732 pounds of oxygen. Allowing a very generous margin for leakage and

inefficiency of blowing cylinders, it is evident that the errors are so great that no instruction can be gained by calculations of the separate periods. Part of the discrepancy may arise from the burning of some carbon to carbonic acid (CO_2). This action occurs when the bath is cool, but most of the carbon is burned during the latter part of the operation, when the temperature of the bath has been raised, and under such conditions carbonic oxide (CO) is the main product. This variation in the gaseous products, in accordance with the thermal conditions, makes the results from any one charge of limited value, but it may be roughly stated that during the combustion of silicon, nearly all the oxygen of the blast is held by the bath, the gases consisting of nitrogen and a small amount of carbonic acid (CO_2), while in the later stages the volume of the products is enormously increased by the escape of carbon as carbonic oxide (CO) and by the expansion due to higher temperature.

The presence of traces of phosphorus in the slag, given in Table 21, has been commented upon by Mr. Howe,* who attributes the phenomenon to a local contamination by shot mechanically held. This is probably not the whole story, for I have found that acid open-hearth slag with 50 per cent. SiO_2 may carry 0.04 per cent. of phosphorus, and this could not all come from shot, but must arise, in part at least, from an absorption of phosphorus by oxide of iron. The failure of the silica to break up the resultant phosphate of iron may easily be explained by the persistence with which traces of elements refuse to be eliminated under conditions which suffice for the removal of all but an inconsiderable proportion. I have elsewhere† dwelt upon this fact at some length.

SEC. 37.—*Variations in the chemical history due to different contents of silicon.*—With a low initial heat, the elimination of silicon is almost complete before the carbon is seriously affected, but there is a certain critical temperature where the relative affinities of silicon and carbon for oxygen are reversed, and, when this is attained, no matter at what stage of the operation, the silicon immediately ceases to have preference, and the carbon seizes the entire supply of oxygen. This

* *Notes on the Bessemer Process. Journal I. and S. I.*, Vol. II, 1890, p. 101.
† *The Open-Hearth Process. Trans. A. I. M. E.*, Vol. XXII, p. 462.

continues until the carbon is reduced to about .03 per cent., but beyond this it is very difficult to go, for these last traces hold on even though the blast be continued with oxidation of iron.

If the metal has contained silicon during the burning of carbon owing to an excessively high temperature, the blowing may be kept up after the drop of the carbon flame and the silicon will be oxidized in preference to iron, but in ordinary practice silicon is eliminated early in the operation, for scrap is added to the charge in sufficient quantity to utilize the excess of heat and prevent the attainment of the critical thermal altitude. The same cooling effect may be attained by the injection of steam into the air supply, but this is less economical than adding scrap, for by the latter method a part of the charge is melted without any extra cost.

It has been the practice at many foreign works, particularly in Germany, to have the pig-iron at a very high temperature in the manufacture of rail steel, and blow "hot" in order to produce a decarburized metal containing silicon. The steel is cooled to a proper casting temperature by the addition of scrap in the ladle, and large quantities of rails and other products have been thus made with from 0.3 to 0.6 per cent. of silicon.

Some pig-iron, notably in Germany and Sweden, contains a considerable proportion of manganese; this burns in some measure at the same time as the silicon, and is usually all eliminated before the carbon begins to oxidize, but at high temperatures, as well as when the manganese is present in large quantity, the carbon has preference. In Sweden this fact is made use of in the manufacture of tool steels, the operation being stopped when the bath is high in carbon, the metal still containing a sufficient proportion of manganese to insure good working. This renders necessary that the silicon content be kept low in the pig-iron in order that none may be left in the steel.

SEC. 38.—*Swedish Bessemer practice.*—The Swedish practice, which stands on an entirely different footing from American and English work, has been thoroughly discussed by Prof. Akerman,* and many of the following statements

* *Bessemer Process as Conducted in Sweden. Trans. A. I. M. E.*, Vol. XXII, p. 265.

are founded on his authority. The pig-iron is made with silicon not much over 1.0 per cent. to insure that the product shall be free from this metalloid even if the blow be interrupted when high in carbon. The charge is taken in a molten state from the blast-furnace to the converter, a practice which has been in general use in Sweden since the first trials of the process in 1857, so that our most modern plants in their use of "direct metal" are simply copying a system which for many years was looked upon as too primitive for advanced metallurgy.

The slow working and small charges which must always characterize the Bessemer practice of Sweden, renders necessary a hot-blowing metal, and since the silicon can not be high without danger of leaving some in the product, it is customary to have from 1.5 to 4.0 per cent. of manganese in

Table 23.

Analyses of Manganiferous Bessemer Pig-Irons and the Resulting Baths and Slags.

Name of Works.	Sample.	Time to beginning of boil.	Time of blowing when samples were taken.	Composition of Metal; per cent.			Composition of Slag; per cent.			
				C	Si	Mn	SiO_2	FeO	MnO	Al_2O_3
Langhyttan.	Pig-Iron.	. . . . .	. . . . . .	3.91	1.14	.64	. . .	. . .	. . .	. . .
	Bess. bath	2m. 45s.	2m. 15s.	4.20	.04	.12	48.76	34.72	13 95	.78
	" "	. . . . .	4m. 30s.	1.10	.03	.12	59.82	21.08	15.48	.98
	" "	. . . . .	5m. 30s.	.05	.01	.06	48.48	35.82	12.29	.72
Nykroppa.	Pig-Iron.	. . . . .	. . . . . .	4.35	.88	1.15	. . .	. . .	. . .	. . .
	Bess. bath	1m. 30s.	2m 30s.	4.10	.10	.15	53.26	13.50	29.76	2.28
	" "	. . . . .	5m. 30s.	1.00	.05	.15	62.34	9.54	23.70	3.90
	" "	. . . . .	6m. 30s.	.08	.04	.08	44.52	30.60	21.39	2.14
Westanfors.	Pig-Iron.	. . . . .	. . . . . .	4.22	1 06	5.12	. . .	. . .	. . .	. . .
	Bess. bath	2m. 30s.	4m. 15s.	4 20	.43	3.26	45.87	4.20	46.38	3.08
	" "	. . . . .	8m. 35s.	1.30	.12	.85	39.07	6.24	52.26	2.49
	" "	. . . . .	9m. 20s.	.55	.07	.43	37.63	9.45	48 92	2.94

the pig. Table 23 gives analyses of metals and slags at different periods of the operation, the data being taken from the paper by Prof. Akerman just referred to.

It will be seen that when manganese was present in large proportion, there was quite an amount left in the steel after the boil had begun and even after most of the carbon had been eliminated. This will be further illustrated by Table 24, which gives additional results from the Westanfors Works, and which is also taken from the paper by Akerman.

The presence of oxide of manganese renders the slag more fluid and also reduces the content of iron oxide, as is clearly

shown by the analyses of the Westanfors slags. This is in accord with the theory elsewhere advanced concerning the composition of open-hearth slags, that after a certain basicity and fluidity are attained, the demand for more bases is not urgent (See Section 70).

SEC. 39.—*History of the slag in the converter.*—Prof. Akerman discusses, with considerable fullness, the part which the slag plays in the oxidation of the metalloids, but I have ventured to disagree with him on this point.* In the open-

TABLE 24.

Examples of Bessemer Steel Made from High-Manganese Pig-Iron by Interrupting the Blast before Complete Removal of Carbon.

Pig-Iron with 4 per cent. Mn and 1 per cent. Si.

Element.	Composition, per cent., of various heats.							
C	1.3	1.1	0.9	0.7	0.5	0.3	0.2	0.15
Mn . . .	0.6	0.55	0.5	0.4	0.3	0.2	0.15	0.12
Si	0.06	0.05	0.045	0.045	0.04	0.03	0 02	0.015

Pig-Iron with 5 to 6 per cent. Mn and 1 per cent. Si.

Element.	Composition, per cent., of various heats.				
C	1.3	1.1	0.9	0.7	0.6
Mn . . .	1.25	1.05	0 9	0.7	0.6
Si	0.25	0.2	0.15	0.12	0.1

hearth process, the history of the slag is the history of the operation, for all the changes in the composition of the metal must of necessity be done through the mediation of the slag, but in the Bessemer the blast enters from the bottom and passes upward through the metal before it ever comes in contact with the slag. It is quite true that the charge is in a state of violent ebullition and that the slag is constantly carried down into the metal, but, nevertheless, such a mixing does not seem to be a necessary and inherent part of the operation, for, when the heat is first turned up, the silicon is immediately oxidized although no slag is present. In short, the question almost resolves itself into a *reductio ad absurdum*, for it is the oxidation of the silicon which first creates the slag, and hence it can hardly be that slag is necessary for the

* *Trans. A. I. M. E.*, Vol. XXII, p. 667.

oxidation of silicon. It is quite true that the slag does automatically adjust its own composition, but probably with much less precision than in the open-hearth furnace.

In American practice no attention is paid to the composition of the slag, for at most works the iron contains only a trace of manganese, while at others it hardly ever exceeds 0.50 per cent., this amount rendering the slag somewhat more fluid, while, with a content much above this, there is considerable loss of metal by slopping. Whether the initial metal contains manganese or not, there will always be a certain proportion in the final slag from the reaction with the recarburizer. An average sample was taken of about one hundred heats at the Pennsylvania Steel Company's works, and the results are given in Table 25 in comparison with the analysis

TABLE 25.

Composition of American Bessemer Slags.

Composition, per cent.				Origin of Sample.
SiO_2.	FeO.	Fe_2O_3.	MnO.	
62.20	17.44	2.90	13.72	Chicago (See Table 21).
59.70	19.30	. . . . .	12.00	Steelton (average of 100 heats).

of Chicago slag as given in Table 21. No attempt was made to separate the different iron oxides, the metal being all calculated as FeO.

The composition of the slag is sometimes greatly changed in one or more charges by the practice of blowing with the vessel partly tipped over while the carbon is burning. This position brings some of the tuyeres above the level of the metal, so that the blast rushes over the surface, oxidizing considerable iron, and also burning part of the CO to CO_2. Under ordinary conditions, the gases escaping from the mouth of the converter during the boil consist of N and CO, but when a part of the air enters just above the metal and the rest from below, as it will do if the vessel is inclined, there will be a greater calorific development, so that this method is taken to raise the temperature of a cold charge at the expense of a greater waste of iron, and a greater wear of the lining.

These cold charges may arise from too low a content of silicon, from a low initial temperature, or from a newly-repaired vessel. It is unusual in our rapid American practice to have much difficulty from insufficient heat, for it is not uncommon to make six, seven, or even eight heats per hour from a pair of 5 or 8-ton vessels, and turn out from 25,000 to 30,000 gross tons of ingots per month. Under these conditions a content of one per cent. of silicon in the pig-iron, without any manganese, is found sufficient for the production of the necessary heat. Little attention need be paid to the initial content of carbon, for, as it burns only to CO, and as the nitrogen and carbonic oxide must both be

TABLE 26.

Calculation showing the Calorific History of the Acid-Bessemer Converter.

(Note: 1 calorie will raise the temperature of 1 Kilo Water 1° Centigrade.

Data assumed: Composition of pig-iron, Si=1 00 per cent. C.=3.50 per cent. 1000 kilos pig-iron contain 10 kilos Si and 35 kilos C. Initial temperature, 1400° C. Average temperature during blow, 1600° C. Specific heat per kilo: C=0.241; CO=0.2479; O=0.218; N=0.244; FeO=0.17; melted pig-iron 0.11; melted steel=0.16. Metallic Iron burned=2.0 per cent. of bath.

	Heat measure in Calories.		
COMBUSTION OF SILICON.			
10 kilos Si+11.4 kilos O develop		78300	
Absorbed by oxygen, 11.4×.218×1600	3976		
Absorbed by nitrogen, $11.4\times\frac{77}{23}$=38.2×.244×1600	14913		
Total heat absorption in the combustion of silicon		18889	
Net heat evolution from silicon			59411
COMBUSTION OF CARBON.			
35 kilos C+46.7 kilos O=81.7 kilos CO developing		83555	
Absorbed by oxygen, (81.7×.2479) 1600—(35×.241) 1400	20596		
Absorbed by nitrogen, $46.7\times\frac{77}{23}$=1563×.244×1600	61020		
Total heat absorption in the combustion of carbon		81616	
Net heat evolution from carbon			4939
COMBUSTION OF IRON.			
20 kilos Fe+5 7 kilos O=25.7 kilos FeO developing		24020	
Absorbed by oxygen, (25.7× 17) 1600—(20×.11) 1400	.3910		
Absorbed by nitrogen, $5.7\times\frac{77}{23}$=19.1×.244×1600	7457		
Total heat absorption in the combustion of iron		11367	
Net heat evolution from iron			12653
Total heat evolution from silicon, carbon, and iron			77003
Heat necessary to raise 1000 kilos of steel 1°C.=1000×.16			160
Increase in temperature of bath of 1000 kilos of steel produced by 77003 calories $=\frac{77003}{160}$=481° Cent.			

heated to the full temperature of the charge, with the absorption of a large quantity of energy in their free expansion, the combustion of this element supplies very little heat to the bath. In the burning of silicon, on the contrary, the only gas escaping is the nitrogen, and with the exception of the calorific power necessary to heat this gas and the silica to a yellow heat, the entire energy of the action is utilized in the bath.

SEC. 40.—*Calorific history of the acid-Bessemer converter.*—The calorific history of the acid-Bessemer bath may be understood from Table 26, in which it is assumed that the energy available for heating the bath is that produced by the combustion of silicon, carbon, and iron, *minus* the heat absorbed in raising the products of that combustion to the temperature of the bath, the amount thus absorbed being the total sensible heat in the products *minus* the heat in the initial metal due to the heated state of the above elements. The initial temperature is taken as the starting point, notwithstanding that at the time when the carbon begins to burn the bath is hotter than at the beginning, for such an increment must be produced by the combustion of some of the elements, and all the heat of that combustion is assumed to be imparted to the metal. It is also supposed that the average temperature of the bath during the operation is 200°C. above the initial heat.

The assumption that two per cent. of iron is burned to useful purpose, is founded on the fact that the Bessemer department at the Pennsylvania Steel Works produces about 120 tons of vessel-slag for every 1000 tons of pig-iron. This slag, after being cleaned by the magnet, averages 15 per cent. of iron, so that the loss is 1.80 per cent. of metal. The volume of slag is determined in great measure by the amount of silica available for each heat, and this silica comes from the wear of the lining, from erosion of the bottom, and from combustion of silicon. The percentage of the latter element in the pig-iron used in the above practice is about 1.75 per cent., which is somewhat higher than is essential, so that scrap must be used to cool the charge. If the pig-iron were supposed to contain only 1.00 per cent. of silicon, the weight of the slag will be considerably reduced, but as the wear of the bottom and lining will remain nearly constant, the decrease will not be proportional. It will be assumed in the present calculation that 1.5 per cent. will represent the usual loss of combined iron in the cinder.

A part of the metal enters the slag as shot, a separation by the magnet giving an average content of from 6 to 8 per cent., indicating a loss of about three-quarters of one per cent. of the total output, and this portion is a complete loss as far as both product and heat are concerned. The large

pieces of scrap in the vessel slag may be picked out by hand, and, as these are generally returned to the cupolas without reweighing, they are not reckoned in the percentage of loss. The smaller particles can only be recovered by the rather expensive process of crushing the slag and passing it over a magnetic separator.

There is about 10 per cent. of loss in the converter in ordinary practice, of which the metalloids do not give over 5 per cent., so that about 5 per cent. of metallic iron must be accounted for. The amount combining with the slag has been shown to be about 1.8 per cent., while the shot is 0.75 per cent., so that from 2.5 to 2.75 per cent. of metal must be ejected from the nose of the vessel by the force of the blast in the form of fine dust and splashes. Most of this metal is oxidized outside the converter, but a part of it is burned within and gives its heat to the charge. Together with the 1.5 per cent. which enters the slag, we may assume that 2 per cent. in all is available as fuel.

Sec. 41.—*Use of direct metal.*—It has been the custom in Sweden, from the earliest days of the Bessemer process, to use the pig-iron as it comes from the blast-furnace without allowing it to become solid, while in other countries it was almost invariably found, during the early history of the art, that it was more economical to remelt the iron in cupolas. The success of the Swedish metallurgists arose partly from the necessity of saving fuel in a country where coal was not to be found, and partly from the favorable character of the native pig-iron, which, being made from charcoal, never contained high silicon, and which was almost always low in both sulphur and phosphorus owing to the purity of the ore and fuel.

Moreover, a large proportion of the Swedish Bessemer product has been, and still is, a very hard steel, the blow being interrupted when the metal contains a considerable percentage of carbon, and therefore the operation can be conducted at a lower temperature, and a lower content of silicon is necessary. The manufacture of this hard steel is made practicable by the low phosphorus and low sulphur in Swedish irons, and although the method of interrupting the blow gives

very irregular results, it will generally happen that the steel is suited for some purpose, and it can be graded after it is made.

The failure of the direct metal process in other countries arose from the fact that the product of a furnace on one day contained so much silicon that the charges were too hot, on another day the silicon was too low and the blows were too cold, while on the third day the iron was so high in sulphur that the steel was worthless. By allowing all the iron to become cold, and by mixing the different qualities according to fracture, and, at a later period, according to chemical composition, it was possible to get a more regular metal which would represent the average product of the furnace. It was also possible to mix the iron from different furnaces, certain brands being prized on account of their hot-blowing or their cold-blowing qualities, when the reason for their peculiarities was unknown.

The conditions in later years have altered the economic situation, and modern practice has reverted to the more primitive system of using the metal directly from the blast-furnace. This change has been made feasible in great measure by improved blast-furnace practice, but even now the product of a single furnace sometimes varies from cast to cast much more than is desirable for regular results in the Bessemer converter.

This irregularity in the character of the pig-iron is provided against at some works by having a reservoir holding one or two hundred tons, always kept full, into which the products of several furnaces are poured, and from which the average metal is drawn when needed. This arrangement renders almost impossible any sudden changes from charge to charge, either in the temperature of the iron or in its composition, and it bids fair to become the universal practice, both in this country and abroad, for acid and basic Bessemer plants.

In some works the percentage of silicon in every cast is determined while the iron is on its way from the blast-furnace to the mixer, so that the blower can be forewarned of any change which is about to take place in the character of the iron. Much information is also gained by a fracture test

made upon a small ingot which is cast in an iron mold, every precaution being taken to have all the conditions of pouring as uniform as possible.

SEC. 42.—*Use of cupola metal.*—The full benefits of the direct metal process can only be obtained by a works possessing more than one blast-furnace, and making a large output. It is also desirable that these furnaces should be within a convenient distance, say two miles, of the Bessemer department, for, otherwise, there will be considerable loss from chilling. For these reasons there are some plants which still remelt all their iron. The cupolas used for this purpose are practically alike in different localities. They measure from 6 to 8 feet in internal diameter, while the height should be at least 20 feet, and can better be 30 feet, to save fuel.

Formerly there were about 8 tuyeres, about 5 inches in diameter, but the tendency has been toward an increase in the number to thirty or forty, the size being correspondingly reduced. The blast pressure is about 12 ounces per square inch. One cupola will melt from 200 to 250 tons in 24 hours and will run about 72 hours. The consumption of fuel varies according to the height of the cupola, and according to the management, one pound of coke being required for 11 pounds of iron in some works, while in other establishments a ratio of 15 pounds of iron to one pound of coke has been attained. This coke must be as free as possible from sulphur, for it is not unusual to have the content of sulphur in the pig-iron raised .02 or even .04 per cent. during the melting.

TABLE 27.

Loss of Combined Iron in Cupola Slag.

Pig-iron charged, pounds	835,600
Coke "	75,750
Limestone "	15,250
Cupola slag "	40,200
Fe in slag, per cent	8 77
Fe in slag, pounds	3529
Fe in slag, per cent. of pig-iron charged	0.42

About half of one per cent. of silicon and some manganese are oxidized during the melting in the cupolas, but these are of little importance when compared with the loss of metallic iron. The total difference in weight between metal charged and metal tapped includes the sand which was attached to

the pig, the silicon, manganese, and carbon which have been eliminated, and also the scrap and shot which freeze to the lining, or fall through the bottom when the campaign is ended.

The true way to find the amount of iron oxidized is to weigh and analyze the cinder running from the slag-hole. Table 27 gives the record for 24 hours on 7-foot cupolas.

SEC. 43.—*Certain factors affecting the calorific history of the converter.*—Aside from the errors involved in the suppositions concerning the burning of iron, the theoretical effects of silicon and carbon upon the operation of the converter are never realized on account of several losses, which may be enumerated as follows:

(1) By radiation and conduction.

(2) By decomposition of the moisture in the blast.

(3) By melting the lining and bottom.

(4) By excess of air passing unaffected through the metal; for even though such excess may burn the CO in the upper part of the vessel to CO_2, a large part of the heat thus produced is carried away in the waste gases rather than absorbed by the bath.

It would be very difficult to make a quantitative estimate of these disturbing factors, and it would be equally unprofitable, for it is easy to obtain sufficient heat without much extra expense by a slight increase in the content of silicon in the pig-iron.

Until within a few years it was thought necessary to have from 2.0 to 2.5 per cent. of silicon in the metal as it entered the converter, but the general practice at the present time is to have from 1.0 to 1.5 per cent., while in the case of one American works the average run of cupola metal contains from 0.6 to 0.8 per cent.

This reduction of the calorific power has been made practicable by several improvements in practice, none of them of overwhelming importance, but which form a considerable total when added together. Some of these details may be enumerated as follows:

(1) Fast and continuous running, the iron never standing long enough to cool, and the steel ladles and vessels being always hot.

(2) Quick blowing, the radiation from the vessel being proportionately decreased, and the time lessened during which the companion and idle vessel is cooling.

(3) Good bottoms and vessel linings, the heat required to fuse the scorified material being correspondingly reduced, and delays for repairs avoided.

(4) Quick changes of bottoms, less cooling of the vessels occurring while putting on a new section.

(5) The practice of blowing with the vessel partly tipped over when the charge is cool, as described in Section 39. It was formerly necessary to have an excess of calorific power in the iron in order that there should be a margin of safety when there was a delay or when a bottom was changed, but the expedient of blowing with the vessel inclined is now in general use, and, to some extent, has rendered this margin unnecessary.

It is the opinion of some metallurgists that this decrease in the initial content of silicon has resulted in a better quality of steel, and Ehrenwerth has endeavored to show why this should follow. His argument may be presented thus:*

When a high content of silicon is used, it is found that there is a greater proportion of free oxygen in the gases which escape from the converter during the first stages of the blow. This change in chemical relations arises from the fact that the percentage of carbon is nearly constant in all irons, and, therefore, with an increase in silicon, there is a corresponding increase in the proportion which the silicon bears to carbon, and a corresponding change in the affinities.

Granting that the presence of free oxygen in the gases escaping from the vessel during the first part of the process is due to the proportionately greater quantity of silicon as compared with carbon, then it would naturally be expected that, if the metal at the end of the operation should, for any reason, contain a high proportion of silicon as compared with its content of carbon, the escaping gases would contain free oxygen.

This proportionately high silicon at the end of the operation is found in heats which contained a high initial percentage of silicon in the iron, and hence such heats would be

* *Das Berg- und Hüttenwesen auf der Weltausstellung in Chicago.* Ehrenwerth, 1895, p. 276.

expected to have free oxygen in the gases which are formed at the close of the operation, and this free oxygen will signify a more highly oxidized and therefore an inferior condition of the metal.

Notwithstanding the argument, which has just been advanced, that the practice of tipping the converter in the case of a cold-blowing charge has rendered unnecessary as large a margin of calorific power as was formerly necessary, it still remains true that it is advantageous, and that it is customary, to have a slight excess of silicon to allow for delays and new bottoms. It is necessary, therefore, to lower the temperature of normal charges by the addition of steel scrap or solid pig-iron, the amount so added being determined from the behavior of the preceding charge, with allowances for any change in the thermal conditions.

The skill attained in estimating the temperature of melted steel seems almost incredible to the lay mind, for when the iron is very regular and all other conditions are uniform, it is possible to detect the difference caused by a variation of 100 pounds in the amount of scrap added to a 7-ton charge in the converter, and I have elsewhere* tried to show that this represents a difference of only 13° C.

It must be acknowledged that all heats are not regulated to such exact measure, but a variation of three or four times this amount is as much as is considered allowable, and more than is expected in current American practice. This accuracy can only be obtained by regular and uninterrupted work, so that we naturally would assume, and, as a matter of fact, do actually find, that the best "scrapping" follows the fastest running.

This fact alone is an all-sufficient answer to the criticism of foreign metallurgists that the large outputs of American Bessemer plants have necessarily been made at the expense of quality. There is absolutely no evidence to show that an ample supply of air, and a consequent shorter blow, will give an inferior product. On the other hand, the more rapid action renders possible a lower initial content of silicon, and this is thought to be an advantage.

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*_The Open-Hearth Process. Trans. A. I. M. E._, Vol. XXII, p. 392.

Aside from this one item of short blows, there is not a single feature necessarily connected with a heavy output which is open to criticism. A large product means simply that no time is lost; that one blow begins when another ends; that the vessel linings are in good condition; that bottoms are quickly changed; that the vessels are always ready for the iron, and the iron ready for the vessels; that the spiegel cupolas work with regularity, and furnish the recarburizer as soon as it is needed; that the steel is of the right temperature so that the ladles are neither burned through nor sculled, and the pit is free from "messes"; in short, that the machinery is ample, and the men capable. In spite of any statements to the contrary, the fact remains that the fast work of American plants sacrifices nothing but energy and brains.

Sec. 44.—*Recarburization.*—The method of recarburizing in Bessemer practice varies with the character of the product. In making soft steel, solid ferro containing 80 per cent. of manganese is thrown into the ladle during pouring, the loss of metallic manganese being about 0.2 per cent. of the charge. With rail steel it is customary to add melted spiegel-iron either in the vessel or in the ladle, but sometimes solid ferro is used to supply manganese, melted pig-iron being poured into the ladle at the same time to give carbon. By this latter method the oxidation of manganese in the cupola is avoided, but the additional danger is encountered of incomplete mixing. When carefully carried out, very little trouble arises from this source, but it is more likely to occur with rail steel than with soft metal, for there is less bubbling and boiling in the higher carbon bath and, therefore, less automatic equalization. The loss of manganese depends upon the condition of the bath and upon the amount which is added. In making soft steel it is necessary to blow until the carbon is reduced to about .05 per cent., and, under these conditions, if manganese be added to the extent of .60 per cent. of the weight of the charge, the steel will contain .40 per cent., being a loss of .20 per cent. If, on the contrary, 1.30 per cent. be added, the steel will contain only .90 per cent., being a loss of .40 per cent.

It seldom happens that soft steel is wanted with over .60 per cent. manganese, but larger proportions are not unusual in

rail steel. In the latter case it is feasible to economize by stopping the blow when the carbon is about .10 per cent., and, under these circumstances, an addition of 1.10 per cent. will suffice to give 0.90 per cent. in the steel. These figures must not be considered absolute, for they are only approximate and represent about what may be expected in the long run rather than on any one heat. A further discussion on this point will be found in the remarks on recarburization in the open-hearth furnace.

CHAPTER VII.

THE BASIC-BESSEMER PROCESS.

SECTION 45.—*General outline of the basic-Bessemer process.*—The basic-Bessemer process consists in blowing air into liquid pig-iron for the purpose of burning most of the silicon, manganese, carbon, phosphorus, and sulphur of the metal, the operation being conducted in a basic-lined vessel, and in such a manner that the product is entirely fluid. The method by which the air is introduced has little effect on the character of the product, but, since it is often necessary to cease blowing temporarily in order to take tests of the bath, the use of a rotary vessel with bottom blast is universal.

The distinctive feature of the basic vessel is a lining which resists the action of basic slags; this is usually made of dolomite, but sometimes a limestone is used containing a very small proportion of magnesia. The stone must be burned thoroughly to expel the last traces of volatile matter and then ground and mixed with anhydrous tar. The bottom is sometimes made by ramming the same material around iron pins which are withdrawn after firing, and sometimes by using ordinary acid tuyere bricks with dolomite rammed between them. These brick tuyeres are cut away quite rapidly by the slag, but they can readily be replaced in the interval between heats. The highest function of the lining is to remain unaffected and allow the basic additions to do their work alone, so that the rapid destruction of a basic, as compared with an acid lining, is not due to any necessary part it plays in the operation, but to the fact that there is no basic material in nature which is plastic, and which by moderate heating will give the firm bond that makes clay so valuable in acid practice. The agent used in its place is a

rich tar, and this forms a strong coke under the action of heat and resists for a long while the scouring of metal and slag, and it generally happens that, by the time this coke is burned, the dolomite has become partially fused and "set." There is always, however, a slight shrinkage in the burned stone, no matter how thoroughly it has been roasted, so that there is an ever-present tendency to self-destruction through the formation of innumerable disintegrating cracks.

When air is blown through pig-iron, the first element affected is the silicon. This is true in both the acid and the basic processes, but the completeness of the elimination is less certain in the acid process, for a part of the silicon is sometimes left after the carbon is burned, owing to the production of an excessive temperature at an early stage of the operation. In the basic converter the incomplete combustion of silicon does not occur owing to three reasons, *viz.:*

(1) The silicon is lower in the pig because the oxidation of phosphorus is relied upon for heat.

(2) Burned lime is added before blowing in order to seize the silica as soon as formed and prevent cutting of the lining, and the heating and melting of this lime absorbs so much heat that the critical temperature can not well be reached, especially since every increase in silicon must be met by a corresponding increase in lime.

(3) The basic slag has a greater affinity for silica than the very silicious slag of an acid converter, and it is probable that under these conditions the critical temperature is raised.

When the silicon is eliminated, the carbon begins to burn and continues until there is only about .05 per cent., while the manganese follows the same course that it does in acid work, part of it being eliminated while the silicon is burning and another part during the combustion of carbon. The proportion of manganese present at any particular time will depend upon the original percentage in the pig, but, comparing similar contents, the amount eliminated will be less than in the acid practice, for there is a less demand for its oxide in a basic slag, and the inducements to oxidation are therefore taken away.

SEC. 46.—*Elimination of phosphorus.*—With the exception

of the basic lining, which is supposed to remain inert, and the basic slag, which has no chance in the early part of the operation to do anything besides aid slightly in the burning of silicon and retard slightly the oxidation of manganese, the reactions in the metal in a basic converter are almost identical with the reactions in the acid vessel up to the point when the carbon is reduced to .05 per cent. From this point comparison ceases, for there the acid process ends, while the basic begins the characteristic chapter in its history in the elimination of phosphorus and sulphur.

In an acid heat phosphorus is always present to a certain extent, and, if blowing were continued, it may be supposed that at the very surface of an air bubble phosphoric acid would be formed which, rising through the metal, would unite with oxide of iron and form phosphate of iron; but this would immediately come in contact with a silicious slag, or, in other words, with a slag possessing more than enough silica to meet the pressing requirements of its bases, and the silica being immediately seized by the oxide of iron, the unprotected phosphoric acid would be robbed of its oxygen by the metallic iron. This may seem a very long explanation of the simple fact that phosphorus does not oxidize, but there are many reasons for supposing that in many chemical actions the atoms are in a state of general translation, so that while many compounds are formed, only those remain which find a suitable environment. It is difficult to explain the formation of phosphoric acid in the basic converter without assuming an action which can just as readily obtain in acid practice, although in the one case the product finds a suitable resting place while in the other it is instantly destroyed.

During the elimination of carbon, a certain small quantity of phosphorus is burned and held by the slag, but for practical purposes it may be assumed that the percentage at the drop of the carbon flame is equal to the initial content. From that time the phosphorus seizes the oxygen in the same way as the silicon and carbon had done before, and the iron is thus perfectly protected, the phosphoric acid immediately uniting with the lime. It might be supposed that any other base like oxide of iron would serve to hold the phosphorus, but it is

found that phosphate of iron is easily reduced by carbon, and that it is in other respects inferior to the oxide of calcium which gives a stable compound.

SEC. 47.—*Amount of lime required.*—The amount of lime needed will depend upon three conditions, *viz.:*

(1) The amount of silicon in the pig.

(2) The amount of phosphorus in the pig.

(3) The quality of the lime.

If the charge is 15,000 pounds, containing 0.50 per cent. silicon, it will produce 160 pounds of silica; and if the final slag must contain 12.5 per cent. silica, then the slag must weigh 1280 pounds; and if it must have 50 per cent. CaO, then 640 pounds of *unsatisfied* CaO must be added. The qualification is inserted that it must be "unsatisfied," for each pound of silica in the lime detracts from its efficacy. Thus, if the lime contains 4 per cent. SiO_2, there will be 4 pounds of silica in every 100 pounds of addition, and if this is to be made into a slag containing 12.5 per cent. of SiO_2 and 50.0 per cent. of CaO, then 16 pounds of CaO is useless as far as it can have any effect upon the metal, since it will be appropriated by its own silica. In this way 20 pounds of the lime out of every 100 pounds, or one-fifth of the total amount, is used in satisfying itself.

The amount of silica derived from the lime and from the silicon does not entirely determine the quantity of lime, for there is evidently a limit to the possible content of phosphoric acid in the cinder. Thus, if a bath of 15,000 pounds contains 3.00 per cent. of phosphorus, it will produce 1030 pounds of phosphoric acid, and if the final slag is to contain 50 per cent. CaO and not over 20 per cent. P_2O_5, then this slag must weigh $5\times1030=5150$ pounds, so that $\frac{5150}{2}=2575$ pounds of CaO must be added to the charge. It is not specified in this case that the CaO shall be "unsatisfied," for it will be immaterial as far as phosphorus is concerned what the silica may be in the lime as long as the demands of silicon are met.

SEC. 48.—*Chemical reactions in the basic converter.*—The qualitative chemical history of the basic converter is shown in Table 28, which gives the analyses of metals, slags, and gases at various stages of the operation, as given by Wedding.

The high percentage of oxygen and carbonic acid in the

gases during the first stage of the operation arises from the chilling action of the basic additions, for at low temperatures carbonic acid is not readily reduced by carbon, but as the metal becomes hotter the carbon assumes more complete command and appears almost entirely in the form of carbonic oxide. At the end of the blow, when phosphorus is burning, the oxygen is held in the bath and the only gaseous product is the nitrogen, so that when the combustion of phosphorus is ended there is no such sudden change in the character of the flame as marks the death of the carbon reaction, and the usual method of determining the purity of the metal is to turn down the vessel when it has blown a certain time and make fracture tests on small sample ingots.

This is, perhaps, the only safe way to tell the critical point in regular practice, but it is quite certain that there is a posi-

TABLE 28.

Analyses of Metal, Slag, and Gases from the Basic-Bessemer Converter: No. 1 = Heat No. 125 at Ruhrort, Germany.* No. 2 = Heat No. 882 at Hörde, Germany.†

Time from Beginning.	Metal.					Slag.						
	Si	C	P	S	Mn	SiO_2	CaO	P_2O_5	FeO	Fe_2O_3	MnO	MgO
Pig Iron No. 1	1.22	3.21	2.183	.080	1.03	...	...	...	...	....	...	...
2m. 46s.	0.72	3.30	2.148	.047	.71	41.15	41.27	0.84	2.40	....	9.03	4.13
5m. 21s.	0.15	3.12	2.224	.051	.50	36.30	39.50	3.12	3.97	0.46	11.02	3.39
8m. 5s.	0.007	2.47	2.157	.049	.18	34.41	42.80	2.99	3.60	0.13	10.72	3.35
10m. 45s.	0.012	1.49	2.096	.051	.16	31.94	43.12	4.02	4.23	0.74	9.94	4.01
13m. 28s.	0.005	0.75	2.053	.051	.14	16.64	44.37	7.15	8.42	4.95	8.51	7.34
15m. 13s.	0.008	0.05	1.910	.055	.01	14.65	46.03	11.60	7.15	3.84	7.39	6.34
19m. 14s.	0.005	0.02	0.230	.060	.01	12.94	47.76	18.83	5.84	3.74	4.25	6.00
19m. 31s.	0.005	0.02	0.139	.055	..	12.20	48.59	18.66	6.79	2.80	4.01	6.26
19m. 49s.	0.004	...	0.087	.056	..	11.71	48.19	18.15	7.19	2.78	4.05	6.38
Rail Steel,	0.01	0.26	0.145	.045	.48	12.77	47.87	16.92	5.94	2.87	4.80	6.75
Pig Iron No. 2	0.58	3.60	2.75	.079	1.57	...	...	...	...	....	...	...
About 3m.	0.28	2.81	2.57	.079	2.50	9.20	76.10	2.94	0.55	....	8.87	4.86
" 6m.	0.07	2.02	2.08	.073	0.30	9.50	71.40	6.90	0.73	....	9.70	5.33
" 9m.	0.07	1.33	2.25	.074	0.34	9.30	66.17	7.32	2.30	....	8.42	6.47
" 12m.	0.06	0.71	1.55	.079	0.26	10.28	50.71	15.87	7.13	....	9.45	6.90
" 15m.	0.02	0.105	0.061	.054	0.21	6.99	46.84	24.73	11.98	....	5.40	4.09
Steel,	0.02	0.136	0.084	.046	0.55	4.79	42.05	16.33	26.03	....	4.62	6.83

Heat No. 882.	Metal.					Gas.				
	Si	C	P	S	Mn	CO_2	O	CO	CH_4	N
Sample 1	.28	2.81	2.57	.079	2.50	3.5	8.1	2.0	0.9	85.0
" 2	.07	2.02	2.08	.073	.30	3.0	3.0	10.6	1.0	81.4
" 3	.07	1.33	2.25	.074	.34	3.0	0.3	28.3	1.6	66.6
" 4	.06	.71	1.55	.079	.26	1.8	0.2	29.8	1.8	65.0
" 5	.02	.105	.061	.054	.21	1.2	0.8	1.6	0.9	95.6

* *Basic Bessemer Process*, pp. 136 and 137.

† *The Progress of German Metallurgy. Trans. A. I. M. E.*, Vol. XIX, p. 366.

tive and visible change in the color and character of the flame as the phosphorus falls below .05 per cent. This alteration is not so sharp that he who runs may read, but I have turned down a large number of heats, made from different kinds of iron, guided solely by this slight change in appearance, and in each case my judgment was corroborated not only by the chemical result, but by the independent observation of an associate.

SEC. 49.—*Elimination of sulphur in the basic converter.*—Sulphur is removed for the most part at the same time as the phosphorus, but, if present in very large quantity, it may be necessary to continue the blast after dephosphorization with the sacrifice of a little iron. In a series of heats made by the Pennsylvania Steel Company, in 1883, a content of 0.25 per cent. was regularly reduced below 0.05 per cent. Manganese was present in this case up to about 2.0 per cent., and this is found to aid in the work, probably by the formation of sulphide of manganese. Even after the manganese has entered the slag it may be available for this function, for it can be reduced by the phosphorus and incorporated into the metal. Table 29 is copied from a paper by Stead* to show the increase of manganese in the bath during a time when there was no addition of this element from outside the vessel.

TABLE 29.

Reduction of Manganese from Slag in the Basic Converter.

(See *Journal I. and S. I.*, Vol. I, 1893, p. 63.)

Heat.	Time of taking test of metal.	Composition, per cent., of the metal in the bath.		
		Mn.	P.	S.
No. 184	Disappearance of spectrum line, At second lime addition,	0.19 0.62	2.070 0.463	0.133 0.067
No. 185	Disappearance of spectrum line, At second lime addition,	0.24 0.81	2.180 0.718	0.072 0.042
No. 186	Disappearance of spectrum line, At second lime addition,	0.24 0.79	2.390 0.483	0.081 0.047

The quantitative investigation of the basic converter is unsatisfactory owing to the fact that a considerable portion of the lime is blown out in the form of dust as soon as the charge is turned up, while at a later time a large amount of

* *On the Elimination of Sulphur from Iron. Journal I. and S. I.*, Vol. I, 1893, p. 61.

slag may be expelled by explosive action, this being particularly marked when the temperature is low. Moreover, the lumps of lime do not immediately become incorporated into the slag and no true sample can be taken. It is, perhaps, from these causes that contradictory statements are made by careful observers.

Wedding states* that there is a volatilization of both sulphur and phosphorus, as proven by the fact that the slags from sulphurous metal do not give correspondingly increased percentages of CaS, while in the cinder from hot charges there will sometimes be from 30 to 40 per cent. less weight of phosphorus than was present in the pig-iron, although a cold blow will show the full amount. On the other hand, Stead†

TABLE 30.

Chemical History of High-Sulphur Iron in the Basic Converter.

(See *Journal I. and S. I.*, Vol. I, 1893, pp. 61 and 62.)

Metal.	Composition, per cent.				
	Initial.	Desiliconized.	Decarburized.	Dephosphorized.	Steel.
Carbon	2.32	2.180	0.07	0.02	......
Manganese	0.66	0.200	0.09	0.06	......
Silicon	1.57	0.300	0.07	trace.	......
Sulphur	0.16	0.148	0.16	0.08	0.07
Phosphorus	1.85	1.920	1.53	0.04	......
Slag.					
CaO	......	44.30	47.00	46.70	......
MgO	......	0.72	0.86	1.80	......
MnO	......	6.60	4.46	2.51	10.79
FeO	......	4.38	8.23	14.02	9.00
Fe_2O_3	......	1.29	1.00	4.29	2.14
SiO_2	......	39.20	29.80	14.90	......
P_2O_5	......	2.61	7.83	14.86	......
S	......	0.16	0.10	0.36	0.36
Probable weight of liquid slag in per cent. of metal	......	7	11	27	......

Quantitative calculation on the Sulphur.

Sulphur in lime used, per cent. = 0.054 per cent.

Sulphur in Slag:	
27 per cent. of slag @ 0.36 per cent. S (see above columns) = per cent.	0.097
Less sulphur in lime added = 15.2 per cent. of 0.054 per cent. = per cent.	0.008
Total sulphur received from metal, per cent.	0.089
Sulphur removed from metal:	
100 parts of initial iron contained, per cent.	0.160
Less 85 parts of blown metal containing 0.080 per cent. S = per cent.	0.068
Total sulphur removed, per cent.	0.092

* *The Progress of German Metallurgy. Trans. A. I. M. E.*, Vol. XIX, p. 367.

† *On the Elimination of Sulphur from Iron. Journal I. and S. I.*, Vol. I, 1893, p. 61.

gives the figures for a basic charge where all the sulphur that was lost by the metal appeared in the final slag. The analyses and summary are given in Table 30.

It will be noted that the calculation rests on "the probable weight of liquid slag" for *one* heat, and this can hardly be considered a final and conclusive proof that volatilization can not occur, or that it does not often occur, or even that it does not usually occur. In another chapter (see Section 89) I have tried to show that such loss of sulphur may take place in open-hearth practice, and, if this is true, it seems probable that it will also hold good in the converter.

SEC. 50.—*Calorific equation of the basic converter.*—An account by Hartshorne* of the practice at Pottstown, Pa., agrees quite well with the data above given for Hörde. The cupola mixture is of the following composition in per cent.: Si, 0.3 or less; S, .03 or less; Mn, 0.80; P, 2.50 to 3.00. From 11 to 13 per cent. of lime is added, and the final slag is of the following composition† in per cent.: SiO_2, 5.10; CaO, 45.26; P_2O_5, 21.37; FeO, 12.00; MnO, 5.56; MgO, 5.90. It will be seen that the specification for the cupola mixture is very rigid, and that the limitations must inevitably result in an increased cost for raw material.

At Hörde about two-thirds of the lime is added at the beginning, so that when the metal is nearly dephosphorized the slag can be decanted, after which the rest of the lime can be put in and the final dephosphorization effected by a purer slag. The first cinder, which is rich in phosphorus and poor in iron, is fit for agricultural purposes, while the second, which is poorer in phosphorus and richer in iron, can be used in the blast-furnace.

The calorific equation of the basic converter may be calculated by the same method that was used in the work on the acid process (see Table 26). The values of silicon, carbon, and iron remain the same, but it will be assumed in Table 31 that the iron contains 0.50 per cent. silicon, and 1.5 per cent. phosphorus, and that 4.0 per cent. of iron is burned to useful purpose.

Of the total production of 114,246 calories, the phosphorus

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* *The Basic Bessemer Steel Plant of The Pottstown Iron Company. Trans. A. I. M. E.*, Vol. XXI, p. 743.

† *Trans. A. I. M. E.*, Vol. XXI, p. 232.

contributes 54,296, or very nearly one-half, and, in spite of cutting down the silicon, the basic iron develops fifty per cent. more heat than was found in the calculation for the acid process (*viz.:* 77,000). A large part of this increase comes from the supposition that 4 per cent. of iron is burned, which is twice as much as was taken for the former calculation. In both cases the figure is an estimate, but it is well known that the basic process gives from 12 to 15 per cent. waste, against 10 per cent. for acid work. This difference arises partly from the phosphorus, but it is also due in some measure to the much greater volume of slag which demands a proportionate supply of oxide of iron, and this metal, so entering the cinder, gives the whole heat of its combustion to the bath.

It is the general practice to use a pig-iron containing one or two per cent. of manganese, and between two and three per cent. of phosphorus, and such a pig would produce a still hotter blow than the one above given, but it is assumed that, if a basic plant were worked up to its capacity, the phosphorus content could be reduced just as in acid work the percentage of silicon has been cut down far below what was once deemed necessary. The basic vessel, however, must always demand a greater development of energy in order to allow for the melting of the lime additions.

TABLE 31.

Calorific Equation of the Basic-Bessemer Process.
Weight of metal=1000 kilos.

	Heat measure in Calories		
Combustion of 5 kilos. of Silicon develop (see Table 26)			29705
Combustion of 35 kilos. of Carbon develop (see Table 26)			4939
Combustion of 40 kilos. of Iron develop (see Table 26)			25306
Combustion of Phosphorus			
15 kilos P+19.4 kilos O=34.4 kilos P_2O_5 developing		86400	
Absorbed by oxygen, 19.4×.218×1600	6767		
Absorbed by nitrogen, $19.4\times\frac{77}{23}$=64.9×.244×1600	25337		
Total heat absorption		32104	
Net heat evolution from phosphorus			54296
Total heat evolution from silicon, carbon, iron, and phosphorus			114246

SEC. 51.—*Recarburization.*—Recarburization is the greatest problem of the basic-Bessemer process, for at the end of the operation the metal contains much more oxygen than an acid bath, while the slag, instead of being viscous and inactive, is very liquid and has a certain amount of loosely held oxide of

iron. In making rail steel by the use of melted spiegel, this oxygen in metal and slag gives a very violent reaction with the carbon of the recarburizer, and the carbonic oxide which is formed reduces a considerable amount of phosphorus from the slag. This action is plainly shown in Table 28, when the content of phosphorus was raised in the case of "pig-iron No. 1" from .087 before recarburization to .145 in the finished product, this latter figure being much too high for good rail steel. The violence of the carbon reaction may be modified in some measure by adding ferro-silicon before the spiegel is put in, so that the oxygen may be taken up by an element which produces no gas.

When making soft steel by the addition of solid ferro-manganese, the rephosphorization is less, but it is still a troublesome factor. In "pig-iron No. 2," Table 28, the silicon is low in the pig, and the slag is rich in bases, yet the phosphorus in the metal was raised from .061 to .084 per cent., giving a content which is too high for the softest grades.

In considering these figures, it must be remembered that Dr. Wedding is not making an argument against the basic Bessemer process; on the contrary, his position would naturally make him its official champion, so that the data in Table 28 may be rightfully cited as fair and representative results of the practice in Germany at a time when this method of manufacture had been in general use for many years.

There have been improvements in later times, and such records could hardly be published to-day as evidence of high excellence. Rephosphorization is now controlled in great measure by keeping the temperature of the metal as low as possible, by using a very calcareous cinder, and by chilling the slag before pouring, so that it can not so readily mix with the steel. This presupposes, however, such a measure of dependence upon personal supervision of every charge, and such perfect control over the working conditions, that uniform success seems too much to expect.

The case of the basic-Bessemer process was ably defended by Joseph Hartshorne* in the discussion of my paper on "Specifications on Structural Steel," but some of the instances cited by him as proof of good practice are open to

* *Trans. Am. Soc. Civil Eng.* Vol. XXXIII, p. 384.

criticism. Thus it is stated that the Rothe Erde Works made 61 heats on one contract, all of which "showed phosphorus between .023 and .093 per cent." In another case the same works made 700 heats, of which 303 were below .06 per cent. in phosphorus, while 67 heats contained between .08 and .10 per cent. This would hardly be considered good work in America, where manufacturers keep their product within much closer limits. Moreover, careful railroad engineers would refuse to accept steel containing over .08 per cent. of phosphorus, while rivet steel is often required to show less than .04 per cent. of this element, it being understood in both cases that the metal is made by the acid process. In the use of basic open-hearth steel, a maximum limit of .04 per cent. of phosphorus is not uncommon for plates and angles.

CHAPTER VIII.

THE OPEN-HEARTH FURNACE.

SECTION 52.—*General description of a regenerative furnace.*—The open-hearth process consists in melting pig-iron, mixed with more or less wrought-iron, steel, or similar iron products, by exposure to the direct action of the flame in a regenerative gas furnace, and converting the resultant bath into steel, the operation being so conducted that the final product is entirely fluid.

Regeneration is specified not because it carries any special virtue, but because it is impracticable to obtain the necessary temperature in any other way. The construction of melting furnaces varies in every place, and no one form can be declared perfect, but in all of them the general principles are the same, as well as the methods of producing and controlling the temperature. Where natural gas is used, and in some instances with petroleum, the fuel is not regenerated, but the air is always preheated. The following description will assume that both gas and air undergo the same treatment. In Figures IV and V are given drawings of a very common type of furnace; its grievous faults will be discussed later, but it may be used to illustrate the method of operation. The gas enters the chamber *F*, which is surrounded by thick walls and filled with brickwork so laid that a large amount of heating surface is exposed, while at the same time free passage for the gas is assured. The air enters a similar chamber, *E*. In starting a furnace the bricks in these chambers are heated before any gases are admitted. With rich fuels, like natural gas, this may not be essential, but ordinary producer gas, when cold, can hardly be burned with air at the ordinary temperature, and an attempt to do so may result in serious explosions,

so that it is advisable to heat the furnace by a wood fire until the regenerators show signs of redness. When finally the gas and air are admitted, precautions are taken to avoid explosions by filling the passages with the waste gases from the wood fire.

The first effect of their entrance is to cool the chambers on the incoming end, for no heat is produced until they meet in the port at *O*. From this point the flame warms the furnace and also the chambers E_2 and F_2, through which the products of combustion pass to the stack. After the brickwork in the first set of chambers has been partially cooled by the incoming gases, the currents are reversed by means of suitable valves, and the gas and air enter the furnace by way of the chambers E_2 and F_2, which, as just stated, have been heated by the products of combustion. It will be evident that on every reversal the temperature of the furnace will be higher, for not only will there be the normal increment due to the continued action of the flame which would obtain in any system, but there is another action peculiar to a regenerative construction, for the gases passing through the chambers are hotter on every change in the currents and, therefore, they will produce a more intense temperature in combustion. Thus in all ways the action is cumulative, and there is a constant increment of heat throughout the whole construction.

In the case of a furnace which has an insufficient supply of fuel and which contains a full charge of metal, the increased radiation at high temperatures, together with the absorption of energy by the bath, may automatically prevent the attainment of too high a heat; but in a good furnace, and more especially in an empty one, the action is so rapid that the supply of gas and air must be carefully regulated in order that radiation can maintain an equilibrium. This necessary control of temperature also places a limit on the heat of the regenerators, so that they are usually of a temperature of about 1800° F. (say 1000° C.). Dissociation plays no part in the practical operation of a furnace, for, with common producer gas and air, both admitted to the valves at a temperature of about 60° F. (16° C.), the melting chamber may easily be made hot enough to fuse a very pure sand into viscous porce-

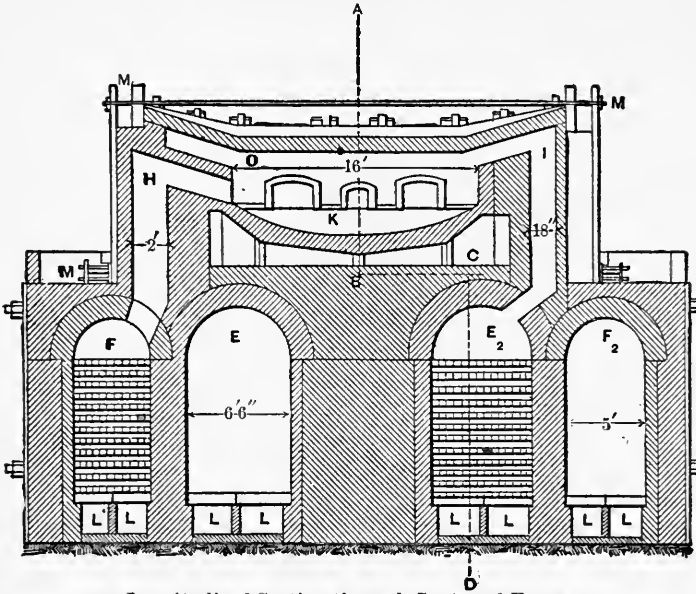
lain. One such specimen of fused material, made under rather unusual conditions, showed the following composition in per cent.: SiO_2, 98.82; Al_2O_3, 0.9; Fe_2O_3, 0.2.

SEC. 53.—*Quality of the gas required in open-hearth furnaces.*—The system of regeneration, which supplies the furnace with a fuel already raised to a yellow heat, renders unnecessary any stringent specifications regarding the quality of the gas. Ordinary producer gas contains over 60 per cent. of non-combustible material, and yet is all that can be desired as far as thermal power is concerned. Certain substances, such as sulphurous acid and steam, are objectionable, but this arises rather from their chemical action upon the metal than from any interference with calorific development. With coal of ordinary quality sulphur causes no trouble, but when it is present in large amounts it is absorbed by the steel.

The presence of steam causes increased oxidation of the metalloids and a greater waste of iron. This oxidation is not always objectionable, since it is sometimes impracticable to obtain sufficient steel scrap, and, if the charge contains an excess of pig-iron, some agent must be used to burn the silicon and carbon. A gas containing hydrogen, like natural gas or petroleum, will be more efficient in this work than a dry carbonic oxide flame, while an excess of steam will make the action still more rapid.

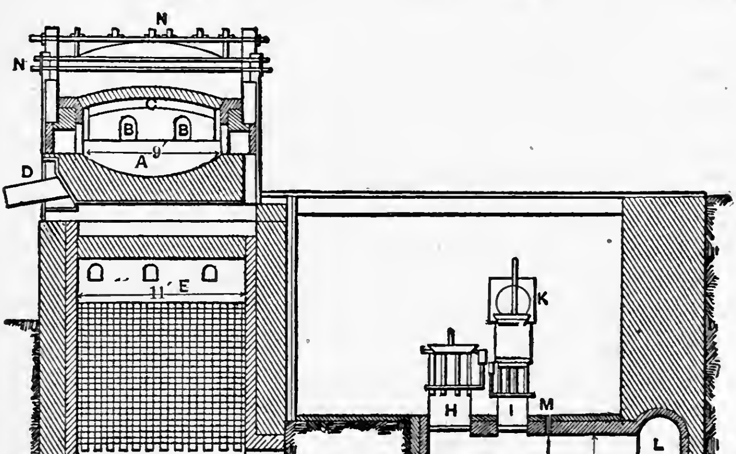
Hence it would be possible to use steam in place of ore as an oxidizing agent, but the practice is not to be recommended. If the steam is used during the melting, a considerable proportion of the oxide of iron which is formed will unite with the silica of the hearth and thus become lost beyond recovery. It is advantageous, therefore, to have no free steam present during the melting of the charge, while after the melting is done the oxygen may be supplied in the form of ore with much more satisfactory results.

The metal at the time of tapping should be as nearly as possible in the condition of steel in a crucible during the "dead melt," and this can only be attained by a neutral flame. In spite of the opinions of many metallurgists, such a flame can not be obtained for any length of time, since it has no active calorific power, and even when black smoke is pouring from the stack, the silicon, manganese, carbon, and



Longitudinal Section through Center of Furnace.
E, E_2, air chambers; F, F_2, gas chambers; H, gas port; I, air port; K, furnace hearth; L, flues to valves; M, M, binding rods; O, meeting place of gas and air.

FIG. IV.—COMMON BUT BAD TYPE OF AN OPEN-HEARTH FURNACE.



Cross Section of Furnace through Line A, B, C, D, of Fig. IV.
A, furnace hearth; B, B, gas ports; C, air port; D, furnace runner; E, air chamber and ports leading to hearth; F, flue to reversing valve; H, air reversing valve; I, gas reversing valve; K, gas box and regulating valve; L, flue to stack; M, stack damper; N, binding rods.

FIG. V.—COMMON BUT BAD TYPE OF AN OPEN-HEARTH FURNACE.

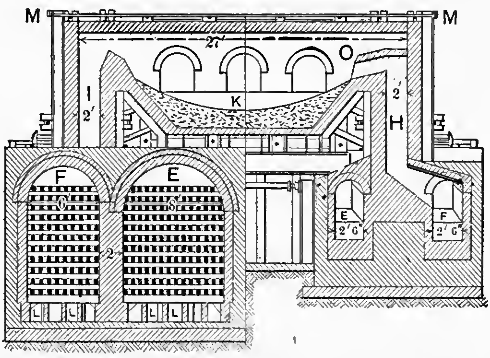
iron are absorbing oxygen from the gases. A carbonic oxide flame can be made more nearly neutral than any other, and hence is more desirable at the end of the operation.

SEC. 54.—*Construction of an open-hearth furnace.*—In the furnace which is exhibited in Figures IV and V it will be noted that the hearth sits partly upon the arches of the chambers. These arches, during the entire run of the furnace, are at a bright yellow heat and are continually subjected to strains and deformation by the alternating shrinking and expansion of the walls that support them. It is needless to say that a poorer foundation for a furnace would be difficult to conceive, and it is a positive certainty that some day there must be a long stop to make what are called "general repairs," this term being often used to cover the alterations consequent upon defective installation. Yet this drawing is copied from one of our leading trade papers as the design of a firm of metallurgical engineers, and, unfortunately, it is the common type erected by many such firms, both in this country and abroad, who are guided partly by ignorance and partly by the necessity of submitting plans for the cheapest construction that will work satisfactorily until their responsibility ceases.

Figures VI and VII show a furnace designed by S. T. Wellman for the Illinois Steel Company, Chicago, and illustrate how this question of foundation may be answered by putting the chambers separate from the furnace. The regenerators are vertical as in the former case, the gases on the way to the furnace entering at the bottom and rising upward through the bricks. This construction renders necessary considerable vertical height, so that either the chambers must be sunk to a great depth, or the charging floor of the furnace must be above the general level and all the stock be elevated. It may seem possible to bring the gas down after going through regenerators, but this is bad practice, for the gases should push themselves into the furnace and they tend to travel upward rather than downward.

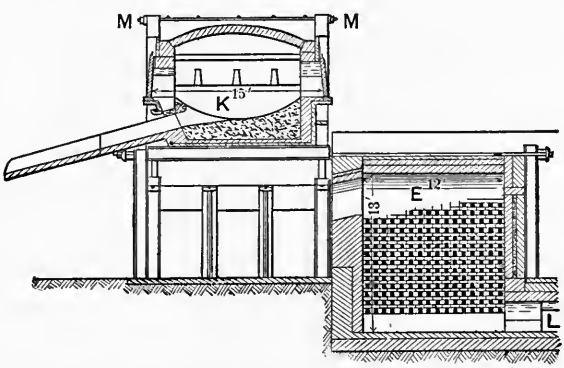
To avoid the cost of elevating the stock, horizontal chambers were devised by H. W. Lash, of Pittsburg. There are objections to them, for the tendency of the hot gases is to seek the upper passages and thus the benefit of the full area is not

secured. In vertical chambers, on the contrary, there is an automatic regulation of the currents; for, if there is a hot place, the ingoing cold gases naturally seek it, and if there is a cold place, the outgoing hot gases find it, and thus there is a constant tendency to equalization and to the highest effi-



View of Longitudinal Section of Furnace showing Chambers and Ports.
E, *E*, air chambers; *F*, *F*, gas chambers; *H*, gas port; *I*, air port; *K*, furnace hearth; *L*, *L*, flues to valves; *M*, *M*, binding rods; *O*, meeting place of gas and air.

FIG. VI.—WELLMAN OPEN-HEARTH FURNACE.



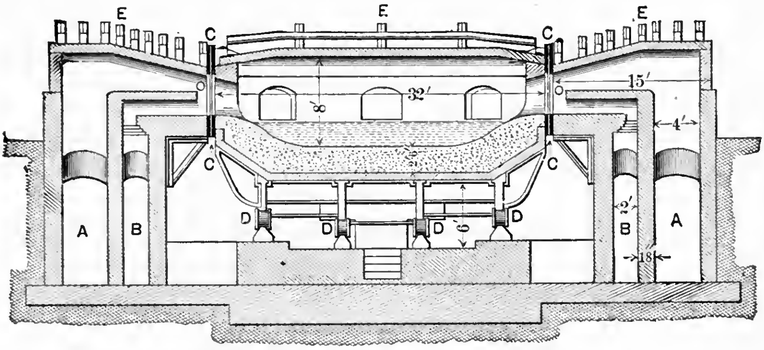
View of Cross Section of Furnace, showing Section of Air Chamber.
E, air chamber; *K*, furnace hearth; *L*, flue to valve; *M*, *M*, binding rods.

FIG. VII.—WELLMAN OPEN-HEARTH FURNACE.

ciency of a given regenerator content. The worst feature of horizontal chambers is the lack of any propelling action upon the gases. With vertical regenerators the hot gas and air rise naturally and force themselves into the furnace, but with horizontal passages there is only a very slight positive pressure

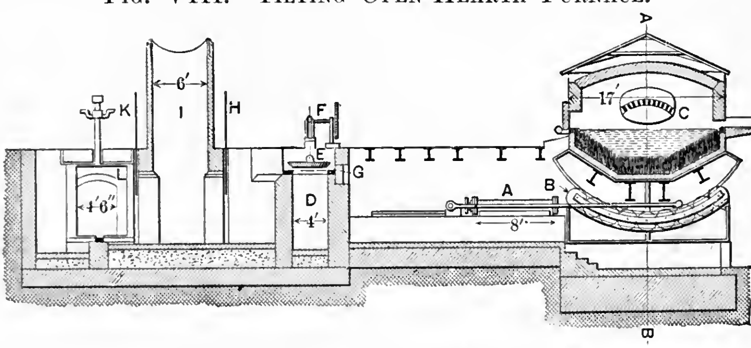
due to the slight uptake near the furnace. The fuel will or should always leave the producer under a slight pressure, so that it will need no further assistance on its way to the furnace, but it is advisable to force the air with a fan blower.

SEC. 55.—*Tilting open-hearth furnace.*—In Figures VIII and IX are given drawings of a type of furnace used by the Pennsyl-



Longitudinal Section through Line *A*, *B*, of Fig. IX.
A, *A*, air flues; *B*, *B*, gas flues; *C*, *C*, *C*, *C*, water-cooled joints; *D*, *D*, *D*, *D*, roller bearings; *E*, *E*, *E*, binders; *O*, *O*, meeting place of gas and air at end of straight arch shown at *C* in Fig. IX.

FIG. VIII.—TILTING OPEN-HEARTH FURNACE.



Cross Section of Tilting Open-Hearth Furnace.
A, hydraulic cylinder for tilting furnace; *B*, roller bearings; *C*, furnace port, showing straight arch; *D*, gas flue; *E*, gas reversing valve; *F*, valve reversing gear; *G*, water-cooled seat; *H*, stack damper for gas; *I*, stack; *K*, stack damper for air; *L*, air reversing valve.

FIG. IX.—TILTING OPEN-HEARTH FURNACE.

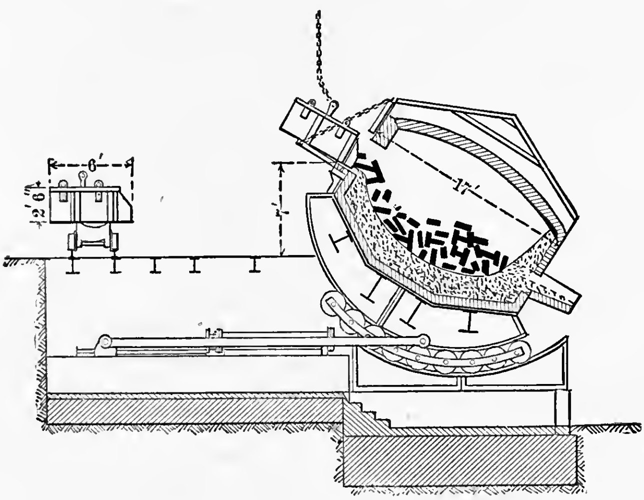
vania Steel Company, Steelton, Pa., since 1889. The horizontal chambers are used to bring the charging floor down to the general level, and the plant is arranged so that narrow and broad-gauge cars run directly in front of the furnace. The air is blown into the chambers by an electric fan. The brick-

work forming the ports is enclosed in iron framework, so built that the whole cage can be changed when the arches are worn out; this is an improvement introduced by C. E. Stafford, of Pittsburg. The furnace itself is my own design. It is placed upon rockers and is tilted by means of hydraulic cylinders, so that it is possible to have the taphole above the metal, since the heat is poured and not tapped as in all other furnaces. By this change much hard and hot work is avoided, for the only labor connected with the hole is an occasional trimming or shaping which can be done at any convenient time. It is customary to keep the opening closed on the outside with a little loose material to exclude air, this being raked out about half an hour before the operation is finished so that the charge can be poured into the ladle when desired. The advantage of this ability to tap instantly will be appreciated in the case of special steels, and particularly in making steel castings when great accuracy in composition is required.

The absence of a taphole is of value for other reasons, for it becomes possible to pour the entire charge into a ladle and then tap the metal back into the furnace, leaving the slag in the ladle. This practice may be employed in acid or basic practice to get rid of the voluminous slag produced in the pig-and-ore process, or it may be used in basic work to remove a very sulphurous, a very phosphoritic, or a very silicious slag, and by thus giving an opportunity for the construction of a new clean cinder, allow a more impure raw material than can be used under any other system. It may also be of great advantage in the transfer of metal from an acid to a basic furnace, or *vice versa*. This idea, which has been proposed numberless times, has always been considered impracticable, but at the plant of the Pennsylvania Steel Company it has been carried out without difficulty, and acid steel can be regularly made with from .010 to .015 per cent. of phosphorus, no appreciable chilling of the charge occurring in the transfer.

SEC. 56.—*Method of charging a tilting furnace.*—One of the most important points connected with the tilting furnace is the economy of labor in charging. At most works the stock is put in by hand, and the work is of the most exhausting character. Charging machines have been devised, but they are very expensive, and there are practical difficulties and costs

connected with the preparatory handling and arrangement of the stock, with the wear of the charging buggies, and with the destruction of the jambs of the charging doors. The furnace above described may be tilted so that the stock can be dropped into the doors from dump-buggies, and by the nature of the case these buggies need not be exposed to intense heat; they may be loaded with scrap at the shears of the rolling mills, and raised and discharged at the furnace by an hydraulic crane. The hearths of both basic and acid furnaces, after the first charge, are as hard as rock, and are not affected by the fall of the most massive pieces of scrap. Figure X is a sketch of the furnace when tilted, showing the method of charging by dump-buggies.



View of Cross Section of Furnace Showing Charging Apparatus.

FIG. X.—METHOD OF CHARGING A TILTING FURNACE.

It will occur to many furnacemen that the back wall may be injured by the stock, but this is prevented by making this wall in the same way as the hearth, by tilting the furnace as far as it will go, and "setting" thin layers of acid or basic material. This wall is, therefore, continuous with the hearth, as shown in Figure X, and, being more infusible and harder than the best of brick, it is never newly rebuilt except when it is necessary to remove the entire hearth.

During the operation of the furnace this back wall wears away to some extent, since it is covered with slag during the tapping. This condition arises from the fact that it is not advisable to decant the slag and metal together, owing to the more violent reaction in the ladle. The furnace is, therefore, tilted, at the beginning of the pour, to such an extent that the slag is above the taphole, and the steel is all drawn off before the cinder. Thus there is a certain amount of scorification of the back wall, but it can be easily repaired when necessary, say once in two weeks, by tipping the furnace and patching in the same way as the rest of the bottom is repaired.

The "setting" of this patchwork must be conducted while the furnace is tipped over to its full extent, else the material will not stay upon such a steep slope, but will run down into the bottom. In order that this can be done, it is necessary that the construction be such that the flame can be kept upon the furnace, no matter in what position it may be. Such an arrangement is of great advantage for other reasons, since it is often convenient to tilt the furnace in order to keep the bath from frothing out the doors, or to drain and patch a hole in the bottom. Moreover, if the practice of dumping the stock be followed, it is necessary that the gas be kept on the furnace while charging, otherwise the cooling would be excessive.

These conditions render it strongly advisable that there shall be an adjustable connection between the furnace and the ports. This is accomplished by the abutting of two water-cooled cast-iron rings (marked CC in Figure VIII), one being fastened to the furnace and the other to the ports. The center of the hole in these rings is the center of rotation of the furnace, and therefore the aperture remains open in all positions of the hearth.

Sec. 57.—*Ports of an open-hearth furnace.*—The working of the furnace depends very much upon the arrangement of the ports through which the gases come and go. The gas should enter below the air because, being lighter, mixture is facilitated, and also because this arrangement does not expose the metal on the hearth to a stratum of hot air and cause excessive oxidation. The point where the two gases meet should be about five feet from the metal; if much less than this, combustion can hardly begin before it is checked by contact with

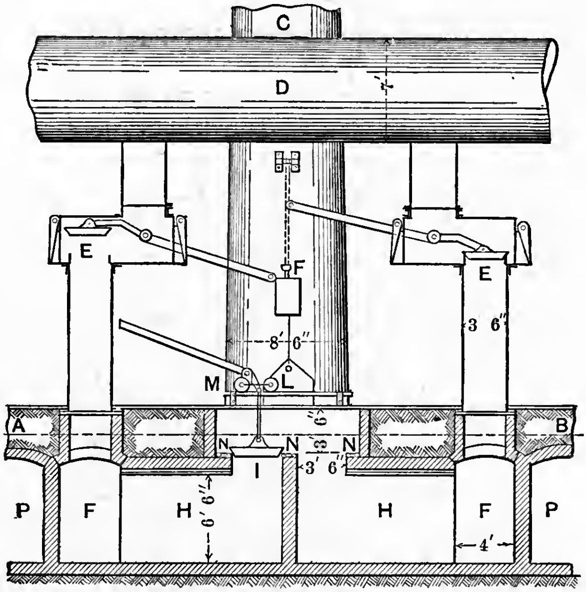
the cold stock; if much more, and if the burning mixture is conducted between confining walls, the brickwork will be rapidly melted.

Both gas and air should enter the combustion chamber under a positive pressure, forcing them into contact with each other and throwing the resultant flame across the furnace in such a way that the draught of the stack on the outgoing end can pull it down through the ports without its impinging upon the roof. A prevalent idea among furnacemen is that the draught of the stack pulls the gases into the furnace, but this is entirely wrong. They are not pulled; they are pushed in by the upward force of the white-hot vertical port on the incoming end, and it has been explained that where this force is not sufficient, as in horizontal chambers, a blower should be used as an auxiliary.

Much has been written about building the roof of the furnace very high and keeping the flame away from the stock, it being supposed that combustion is thereby aided and the heating done more economically by radiation. The suggestion of a high roof is a very good one, as it prevents the cutting of that portion of the furnace; but, contrary to what seems a common impression, such a construction is not necessarily synonymous with heating by radiation. When the ports are properly built and the gases well controlled, the melting is hastened by having the flame strike down upon the stock, although, probably, the oxidizing influence is more powerful.

SEC. 58.— *Valves of an open-hearth furnace.*—The amount of gas and air admitted to the chambers is regulated by some simple form of throttle valve. Reversing apparatus is also necessary, since the course of the currents must be changed at least twice every hour. For this purpose the ordinary butterfly valve is in common use. Its simplicity, the ease with which it is manipulated, the small space it occupies, and its small first cost, have led to its general adoption and to an equally general unwillingness to recognize its radical and irremediable defects. From the nature of the case it is exposed on one side to the incoming gases, and on the other to the products of combustion. It will sometimes happen that these waste gases are red hot, and the inevitable result is a

warping of the valve or box, and a leak from the gas main into the chimney. There is no adjustment possible, and the only remedy is to replace the whole outfit.



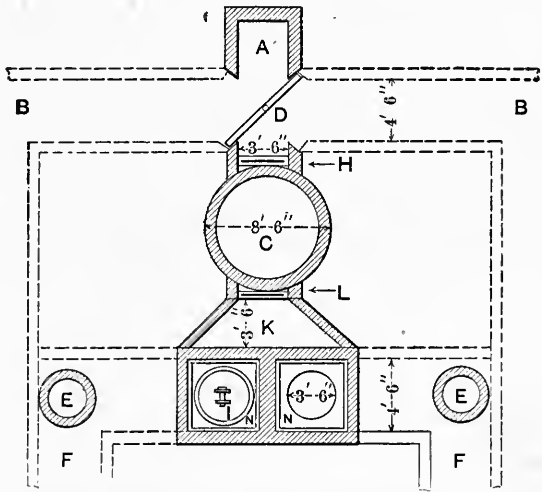
Vertical Section through Gas Reversing Valve.

C, stack; *D*, main gas tube; *E, E*, branch gas tube, showing valve; *F, F*, gas chambers; *H, H*, gas chamber flues to reversing valve; *I*, stack reversing valve for gas; *L*, stack damper for gas; *M*, valve reversing track and buggy; *N, N*, water-cooled valve seats; *P, P*, air chambers.

FIG. XI.—SYSTEM OF GAS AND REVERSING VALVES FOR A REGENERATIVE FURNACE.

It is far preferable to spend more money on the installation and put in valves which will last longer and which can be changed in case any warping occurs. Such a construction is shown in Figures XI and XII. It will be noted that there is only one reversing valve, and that, to change currents, this is carried from one seat to the other. Both of these seats are water-cooled, and the valve is always in contact with a cold surface and is always under exactly the same conditions. The only ironwork necessary is a cast-iron cover-plate with a long slot and a small buggy and chain, which, with two seats and one valve, make the cheapest apparatus that can be built. The slot is always open, but the air that is drawn in goes up the stack and is a benefit in cooling the valves. Such an ar-

rangement may be used for years without the least repair even when oil vapor is used for fuel and red-hot gases escape to the stack. The transfer of the valve is as simple and quick as the throwing of a butterfly.



Horizontal Section on Line *A*, *B*, Fig. XI.
A, air inlet; *B*, *B*, air chambers; *C*, stack; *D*, air reversing valve; *E*, *E*, gas inlets; *F*, *F*, gas chambers; *H*, stack damper for air; *I*, stack reversing valve for gas; *K*, flue from reversing valve to stack; *L*, stack damper for gas; *N*, *N*, water-cooled valve seats.

FIG. XII.—SYSTEM OF GAS AND REVERSING VALVES FOR A REGENERATIVE FURNACE.

SEC. 59.—*Regulation of the temperature of an open-hearth furnace.*—The temperature of the interior of the furnace and of the metal is estimated by the eye, deep-blue glasses being used as a protection from the intense glare. It is essential that the melter possess considerable skill in this line, for if the metal is too cold it can not be cast, and if too hot it will give bad results. I have elsewhere* shown that the practiced eye can detect a difference of 13° C. in the temperature of Bessemer charges, and this may also be taken as the measure of skill to which many open-hearth melters attain.

It has been explained that the intense heat of a regenerative furnace is made possible by the preheating of the gas and air in chambers which have been warmed by the products of

* *The Open-Hearth Process. Trans. A. I. M. E.*, Vol. XXII, p. 392.

combustion, these chambers being alternately heated by currents traveling from the furnace to the valves, and cooled by currents going from the valves to the furnace. If the currents were not reversed, the chambers on the outgoing end would be heated uniformly throughout their length to about the temperature of the furnace, while, at the same time, the chambers on the incoming end would be uniformly cooled to the temperature of the incoming gases. By the reversal of the currents there is a continual conflict between these extremes, so that in a furnace in good working order the ends next the melting chamber are at a bright yellow heat, and the ends next the valves are about 200° F. (say 100° C.) above the temperature of the incoming gases.

Air always enters cold, but it is believed by some furnacemen that it is economical to have the gas delivered to the valves as hot as possible. To some extent this is an error, for it is certain that the checkers in the outer end of the gas chamber can not possibly be cooled below the temperature of the entering gas, and it is just as certain that the products of combustion escaping to the stack can not possibly be cooled below the temperature of these checkers. Hence it follows that if, during a given time, there is an equal quantity of gaseous matter passing through the chamber in either direction, the heat carried in by hotter fuel is carried out by hotter waste gases, and therefore no economy is obtained.

With hot gas, however, it is not necessary to pass such a large proportion of the products of combustion through the gas chambers, and an extra amount may be diverted to the air chambers, where the heat may be used to advantage, so that a certain gain accrues. This gain may be quite important when the coal contains only a small proportion of the denser hydrocarbons, for, under these conditions, the gas leaves the producer at a high temperature; but when the coal is very rich in volatile components, the gas is at a very low temperature when it comes from the fire, and the gain from its immediate use may be inappreciable. It is true that all the tar is utilized when hot gas is used, but it will be shown, in Section 67, that this represents only a small part of the total calorific development.

SEC. 60.—*Calorific equation of an open-hearth furnace.*—

The heat produced by the combustion of the fuel is by no means entirely available in useful work, for it is probable that less than one-eighth of all the energy is consumed in heating and melting the metal upon the hearth. I have elsewhere* recorded the results of an investigation into the distribution of the calorific power in a 24-ton acid furnace, with vertical chambers and a consumption of about 800 pounds of bituminous coal per gross ton of product. Neglecting Sunday work and repairs, the fuel would probably not be over 700 pounds per ton, or an average of 16800 pounds of coal per heat of 24 tons of steel. The operation may be divided into three periods:

(1) The period of making bottom and charging.

(2) The period of melting.

(3) The period of oreing and superheating.

It was estimated that 1512 pounds of coal were burned in the first period, and this can be subtracted from the total, because the loss of heat from the open doors is equal to the gain from the fuel burned. This leaves 15288 pounds consumed in the actual heating, melting, and superheating of the charge, being 637 pounds or 290 kilogrammes per ton. The calorific value of the coal was taken at 8198 calories per kilo, giving a production of 2,377,420 calories per ton. It is shown in Chapter IX of this book that 35.1 per cent. of the value of the coal is lost in the manufacture of gas, leaving available 64.9 per cent. of 2,377,420, or 1,542,950, calories. To this must be added the energy created by the combustion of the silicon, manganese, carbon, and iron of the charge, found by calculation to be 143,000 calories per ton, making a total supply of 1,685,950 calories per ton. The products of combustion were about 300° C. above the temperature of the entering gas and air, and this will account for 16 per cent. of the total potential heat of the gas, or 246,870 calories. Moreover, the analyses of the gases proved that perfect combustion never occurred; that either the escaping products contained a certain proportion of unburned fuel, or an excess of air, or both. These conditions indicate a loss which was put at 4.5 per cent., or 69,430 calories. Calculations on the calorific power theoretically necessary to heat and melt the stock gave about 290,000

* *The Physical and Chemical Equations of the Open-Hearth Process. Trans. A. I. M. E.*, Vol. XIX, p. 18.

calories per ton. By adding these items together and subtracting the sum from the total production of heat, the loss from radiation and conduction was found. Table 32 gives a summary on the foregoing basis.

It will seem rather extraordinary at first sight that in a regenerative furnace, recognized as the highest type of heat utilization in the combustion of gas, only 17 per cent. of the potential power is used and only 12 per cent. of the value of the coal. Experience demonstrates, however, that it takes very nearly as much fuel to keep an empty furnace at a working temperature as it does to make steel, and this indicates that the general truth of the result is not open to question.

The consumption of fuel, in the foregoing calculation, has been assumed to be 700 pounds of coal per ton of product for the actual time of operation. In some of the more modern furnaces this has been reduced to 600, and even to 500 pounds. This result is attained by very large regenerator capacity, and by careful attention to all the details both of producer and furnace practice. In such cases the thermal equation will vary somewhat from the example just given, the greatest change being found in the percentage of heat utilized in melting and heating, while the other factors would probably bear nearly the same relation to one another as when the total loss is greater.

A type of construction which has been tried during the last few years*, presents certain possibilities of fuel economy. The fundamental idea is to divert part of the products of combustion, as they pass from the melting chamber, and inject them beneath the grate of the producer. The carbonic acid and steam, contained in these waste gases, are broken up by the glowing coke and converted into carbonic oxide and hydrogen, and a large part of the energy necessary for these reactions will be contributed by the waste gases themselves if they have not been allowed to cool on their way from the furnace to the producer. I am informed by the proprietors of this device that it has given excellent results on the Continent and in England in puddling, heating, and welding furnaces, and that open-hearth plants are now in process of erection.

* *A New Form of Siemens Furnace.* John Head; *Journal I. and S. I.*, Vol. II, 1889, p. 256.

An attractive modification of regenerative construction, used abroad to some extent, consists in placing the producer very close to the furnace, so that by avoiding all cooling influences, the gas may be delivered to the combustion chamber at such a high temperature that regeneration is unnecessary. Under this practice a steam jet can not be used under the grate, for it will lower the temperature of the fire too much for good results, and it is well known that there is a very much greater loss of fuel, time, and labor, in cleaning fires which are run with dry air than when steam is used to rot the clinkers.

In some localities, as at Witkowitz, Austria, the nature of the coal allows the use of dry blast, the ash being rendered just so viscous by the heat that it can be removed in a ball from the bottom of the producer, but this is an unusual condition, and ordinarily the additional loss of fuel through the grates under the above arrangement will counterbalance, to some extent, the gain from the use of hot gas.

TABLE 32.

Distribution of Heat in an Open-Hearth Furnace.

Production of Heat.	Calories, per ton.	
Heat available for furnace = 64.9 per cent. of 2,377,420,	1,542,950	
Heat from combustion of Si, Mn, C, and Fe	143,000	
Total potential heat	1,685,950	
Loss of Heat.	Calories, per ton.	Per cent. of total.
Loss from sensible heat of waste gases	246,870	14.7
Loss from imperfect combustion and excess of air .	69,430	4.1
Absorbed in melting and heating	290,000	17.2
Radiation (by difference)	1,079,650	64.0
Total loss.	1,685,950	100.0

In the absence of gas regenerators, it will doubtless happen that the air chambers will receive more heat from the furnace than is necessary for the preheating of the air, since all the products of combustion will pass through them. It will follow that there will be a constant quantity of sensible heat passing away from the regenerative chambers, which may be utilized in the production of steam or in other ways. This surplus heat represents the economy resulting from the direct use of the gas.

The foregoing remarks have been confined almost exclusively to the furnace itself, and are of general application

without regard to the specific nature of the operations conducted therein. In dealing with the metallurgical features, there is a natural division into two kinds of practice. In one, the hearth is lined with sand, and the slag is silicious; in the other, the hearth is made of such material that a basic slag can be carried during the operation. This variation creates two entirely different sets of conditions, and gives rise to systems which are known as The Acid and The Basic Open-Hearth Processes.

CHAPTER IX.

FUEL.

SECTION 61.—*Fundamental equations representing the combustion of organic fuel.*—A full definition of the word "fuel," and the correlated term "combustion," would necessitate a journey into the domain of chemical physics. Such a dissertation would not be entirely unprofitable, for in the modifications of the Bessemer process the calorific value of silicon, manganese, phosphorus, and iron are of vital importance, but in the affairs of everyday life the term "fuel" embraces only the various forms of carbon known as charcoal and anthracite coal, and conjunctions of carbon and hydrogen such as natural gas, petroleum, and bituminous coal, while the meaning of "combustion" is also narrowed down to the union of such substances with oxygen. In the case of complex hydrocarbons, like wood, soft coal, or oil, the full history of combustion would be a record of manifold dissociations and syntheses; but for practical purposes it may be considered that in all compounds of hydrogen and carbon there is an isolation of each element just previous to union with oxygen, and the molecular history may, therefore, be represented by the following simple equations:

$$C + 2O = CO_2,$$
$$1 \text{ kilo } C + 2\tfrac{2}{3} \text{ kilos } O = 3\tfrac{2}{3} \text{ kilos } CO_2,$$
producing 8080 calories.

$$CO + O = CO_2,$$
$$1 \text{ kilo } CO + \tfrac{4}{7} \text{ kilos } O = 1\tfrac{4}{7} \text{ kilos } CO_2,$$
producing 2400 calories.

$$1 \text{ cubic metre } CO + \tfrac{1}{2} \text{ cubic metre } O = 2 \text{ cubic metres } CO_2,$$
producing 3000 calories.

$$2\,H + O = H_2O,$$
$$1 \text{ kilo } H + 8 \text{ kilos } O = 9 \text{ kilos } H_2O,$$
producing 34500 calories.

$$1 \text{ cubic metre } H + \tfrac{1}{2} \text{ cubic metre } O = 1 \text{ cubic metre } H_2O,$$
producing 3090 calories.

$$C + O = CO,$$
$$1 \text{ kilo } C + 1\tfrac{1}{3} \text{ kilos } O = 2\tfrac{1}{3} \text{ kilos } CO,$$
producing 2470 calories.

It has been questioned whether this latter action ever takes place, the theory being that carbon always burns first to CO_2 and is then reduced to CO by absorption of incandescent carbon. Whether this is true or not is of little moment, for nothing is gained or lost in calorific energy by the transmutation, and it is, therefore, simpler to assume a direct action.

SEC. 62.—*Functions of a reverberatory furnace.*—An ordinary cupola is the most economical user of fuel, the coke or coal being in direct contact with the substance to be melted, but in many operations with iron and steel it is advisable to separate the solid fuel from the metal. For the heating of cold blooms or billets the same general type of reverberatory furnace is used to-day that was used a hundred years ago. In this construction the products of combustion escape at a temperature considerably higher than that of the metal upon the hearth, so that if a boiler be placed just over the furnace, and the gases pass through it on the way to the stack, the waste heat is quite well utilized during the time that the furnace is at a high temperature; but when there is a full charge of cold blooms, the combustion chamber is so cold that large volumes of unburned carbon pass through unconsumed. Needless to say that the boiler can not make use of this lost power; on the contrary, it will chill the gases and check whatever combustion is still progressing in the smoky mixture. This same action occurs whenever fresh coal is put on the fire, the rich hydrocarbons being thrown off in great quantities and passing unburned through the furnace.

To avoid these losses, many systems are in use by which air is admitted near the bridge wall, and it is usual to preheat this air by passing it through iron or brick flues, which are warmed by

either the furnace walls, the stack, or the hearth. Theoretically this idea is much to be commended, and in practice it often gives good results in an economy of fuel and a hotter flame; but unless intelligently watched there is a chance for serious mistakes in admitting too little air at the time of poking the fire, and too much air when the evolution of the denser gases is lessened. In the latter condition, sharp tongues of flame may play down upon the stock and waste or overheat the metal, so that many mill managers look upon the loss of unburned fuel as an evil which can be met only by invoking the aid of a greater enemy.

When air is used at the bridge, it is plain that the combustion chamber is a gas furnace, the gas coming directly from a sort of producer, called the fire box, and meeting air at a fixed point. When no air is admitted at the bridge, it is still in some measure a gas furnace, for a little air comes through the bed of coal, creeping along the walls or through the holes in the fire, so that combustion goes on throughout a long soft flame. Such a furnace has an advantage in heating cold stock, as the flame is already burning when it comes over the bridge, and not even the coldest combustion chamber can prevent it from exercising a strong heating effect. In a true gas furnace, on the contrary, the gas contains no active oxygen, and combustion is dependent upon a supply of air, and also upon the maintaining of a certain critical temperature which varies with every gas. Rich gases, like hydrogen or illuminating gas, burn at any ordinary temperature when once started, but common producer gas, if thoroughly cold, will hardly keep burning, even when started, if the air is also at a low temperature, so that when a furnace using common producer gas is charged with cold blooms, combustion is greatly retarded. If such a furnace has a great reservoir of heat in regenerative chambers, little trouble will be found with the first charge, or perhaps even with the second or third; but each one takes from the surplus store, and the working goes from bad to worse. For this reason coal furnaces are generally used when cold stock is to be heated; but when hot metal is to be given a wash heat, or when the most intense temperature is desired, a regenerative gas furnace should be employed.

The construction of such furnaces was discussed in the last chapter, while the following paragraphs deal with the kinds of gas used in them.

SEC. 63.—*Use of natural gas as fuel.*—In the favored district lying just west of the Alleghenies in Pennsylvania and Ohio, natural gas has been almost universally used for all kinds of heating from about 1884 until the present time. The composition varies in different wells, but in all cases the gas is made up of members of the paraffine series with not over one-half of one per cent. of carbonic acid (CO_2) and from 2 to 12 per cent. of nitrogen. By ultimate analysis it gives about 70 per cent. of carbon and 23 per cent. of hydrogen, while, by ordinary methods, it shows from 67 to 93 per cent. of marsh gas, the remainder, when the marsh gas is low, being principally hydrogen. At first this gas was passed through regenerative chambers, but this was discontinued owing to the deposition of soot and to the discovery that sufficient heat was obtained by leading the gas directly to the ports and burning it with air which had been regenerated in the usual manner. With the decrease in the available supply of natural gas, and its consequent enhanced value, there is a growing tendency to change to other fuel, and crude oil has seemed to be a desirable substitute, not only in the hope of economy over coal, but from the necessity that the producer plant shall occupy the minimum of space, especially in the heart of an industrial city where land is valuable.

SEC. 64.—*Use of petroleum as fuel.*—Crude oil may be transformed into a vapor by atomizing with steam and then superheating the mixture, but unless exposed for some time to a yellow heat it remains a vapor and hence will condense if carried through long, uncovered pipes or introduced into the cold valves of a regenerative furnace. It may be put into the chambers at some point where the temperature is high, and in this way condensation will be prevented as well as the waste heat be utilized. There is also a partial molecular rearrangement with the steam, but the action is far from perfect, for, after passing through twenty feet of small brick flues at a yellow heat, the product may contain 20 per cent. of free aqueous vapor. The mixture of oil vapor and steam may be

burned in a muffle, for, after the walls are red hot, there is a reciprocal sustention of heat ; but the use in reverberatory furnaces is very wasteful since the action is very sluggish. Even in regenerative practice a charge of cold stock retards combustion much more with oil than with coal gas, and even when at maximum temperatures, the flame is longer on account of there being double work to do before the combustion is complete. Each molecule of oil, as it comes into a hot furnace, undergoes a process of dissociation, the rich hydrocarbons breaking up under the tension of internal molecular activity. This absorbs heat and thus for an instant the action of disruption lowers the temperature below the point of ignition. Moreover, as each point of oil explodes, it makes a small balloon of gas, and it takes a moment for this to become mixed with the air necessary for its combustion. If steam is present its reduction by carbon entails a certain delay.

These matters may seem trifling, but they are probably the explanation of the very important fact that, under the usual conditions of furnace operation, a flame from oil vapor is longer than a flame from coal gas. In the burning of clear carbonic oxide, or a mixture of it with nitrogen, there is no preliminary decomposition to be performed, the air being free to immediately touch and burn the molecules of the fuel.

It is impossible to state the comparative economy in the use of coal and oil, since their relative values vary so widely in different localities. It often happens that the freight on fuel is three, four, five, or perhaps ten times its value at the source of supply, and it will be evident, since oil contains so much more calorific power, that the freight per unit of heat value becomes less and less, compared with coal, as the absolute transportation charge increases; so that if both were to be carried fifty miles, coal might be much the cheaper, while if the distance were a thousand miles, the status would be just the reverse. A rough comparison may always be made by assuming that 50 gallons of oil are equivalent to about 1000 pounds of soft coal when used in regenerative furnaces or under boilers. In the latter case, the success of the practice depends upon the arrangements made to prevent chilling of the flame before vigorous combustion is in progress.

SEC. 65.—*Use of water gas as fuel.*—If steam is passed through a bed of incandescent carbon, the following reaction occurs:

$$C + H_2O = CO + 2H.$$

Both of the resultant products are of the highest value, and this method of manufacturing a gas of intense calorific power has always appeared to the inventive mind a field for profitable inquiry. There are, however, one or two plainly evident difficulties, for the reaction above given calls for a great absorption of heat and, therefore, the fire is rapidly cooled. To bring up the temperature again a blast of air is necessary, and then the fire makes only common producer gas containing 60 per cent. of nitrogen, so that the process must be intermittent and the rich and poor gases be collected separately.

The most successful apparatus for this work has been devised and developed by Mr. Burdett Loomis, of Hartford, Conn., and his engineer, Mr. Pettibone. In their arrangement soft coal is generally used and the steam is on about half the time, while during the other half combustion is urged by a stream of air pulled downward through the fire. This down-draught prevents the caking of the coal, converts the volatile matter into a fixed gas, and also allows the opening of doors above the fire, giving the best of chance for feeding coal where it is needed and rendering poking unnecessary. The upper part of the fire is hottest, and the steam which is admitted at the bottom, and which is heated to a high temperature by passing through the lower portions, is completely broken up by meeting the upper zone of incandescent carbon.

The sensible heat of the products is utilized in generating steam to run the plant and no water-cooled valves are needed. The gas made with the air draught can be used for ordinary heating purposes in regenerative furnaces, while the water gas may be burned without preheating, and, being under a positive pressure and of high calorific power, can be distributed in small iron pipes. It is especially valuable when the work is intermittent, for in such cases a regenerative furnace is unsuitable, since it requires nearly as much fuel to keep it at a maximum temperature when empty as when it is charged, while water gas can be turned on or off as needed, and an intense heat quickly produced.

It will be seen that these considerations have no bearing upon regenerative work, for it costs nothing to pass gas through checkers, and it is, therefore, no advantage to have a fuel which does not require such preheating. It is probable that the open-hearth and the rolling mill will continue to use whatever gas furnishes a given number of heat units at the least cost, without regard to the calorific power per unit of weight or volume.

SEC. 66.—*Use of anthracite coal for making fuel gas.*—Hard coal is admittedly less desirable than coke in the blast-furnace and cupola, and far inferior to soft coal in the reverberatory furnace, but when used under boilers it is equal to the bituminous variety both in facility of working and in the quantity required. Anthracite has also been successfully used in the production of gas where high calorific power is not essential, the gaseous products being composed almost wholly of carbonic oxide (CO) and nitrogen.

Such a bed of coal, if run by forced draft, becomes unmanageably hot, so that steam is injected at the grate, and this rots the clinkers, cools the fire, and is decomposed by the carbon as in the manufacture of water gas, but the amount that can be used is limited, an excess lowering the temperature so that much steam passes through unaffected.

For the sake of economy the small sizes known as buckwheat and pea coal are used, special arrangements being introduced to avoid trouble in cleaning fires; under these conditions a gas may be regularly produced of about the following composition:

	Per cent. by volume.
CO	27.0
H	12.0
$CH_4 + C_2H_4$	1.2
CO_2	2.5
N	57.3

This is nearly the same result that will be obtained in a soft-coal producer, but, when the attempt is made to substitute the one for the other, it is found that while gas from anthracite is nearly equal in producing low temperatures, such as firing boilers or drying ladles, it is far inferior, if not entirely valueless, in creating an intense heat even when properly regenerated; it is supposed with much reason that this inferiority lies in the absence of the suspended and vola-

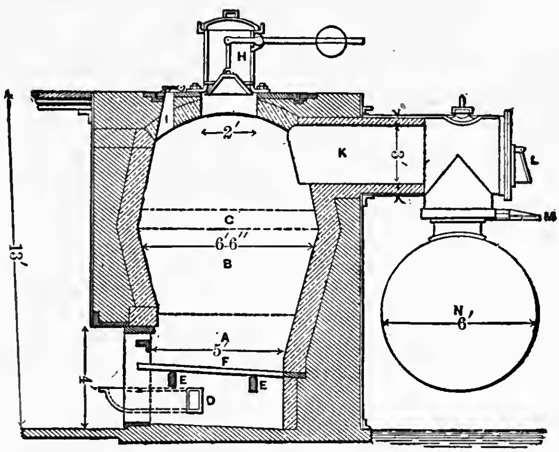
tilized tarry matters which are characteristic of soft-coal gas. These components have quite an appreciable heating value, but their main function is to give luminosity to the flame and, by increasing its power of radiation, augment enormously its practical value. This point is taken up more fully in the consideration of the Siemens producer.

SEC. 67.—*Use of bituminous coal for making fuel gas.*—The conversion of soft coal into gas is performed by burning it in a thick fire and collecting the gases evolved. One of the most common devices to carry out this work is the Wellman modification of the old Siemens producer, a drawing of which is given in Figure XIII. In a group of such fires all discharge into the common tube *N*; but aside from this each is built independent, being surrounded by a circular shell of steel, insuring a permanent preservation of the shape of arches and walls, and rendering impossible a leakage from one fire to another. Air is blown in beneath the grate to force combustion, and a jet of steam is also admitted to keep down the temperature and prevent the formation of clinkers.

It will be seen in Figure XIII that the body of the producer is divided into unequal zones, marked *A*, *B*, and *C*. The division *A* represents the layer of ashes, varying in thickness from nothing to three feet. This layer must be taken into account in estimating the actual depth of the fire. The zone *B* is the region of combustion where the air meets glowing carbon and forms carbonic acid (CO_2), and this, rising through the bed of coal, absorbs more carbon and becomes carbonic oxide (CO), but this action is never complete and some carbonic acid passes through the fire unchanged. With a hot deep fire, free from cavities, the gas may contain as low as 2.5 per cent. by volume of CO_2, but if the fire be thin, or if it is riddled with holes, there may be as much as 10 per cent.

It is also in the "zone of combustion" that the steam is broken up by the carbon with formation of hydrogen and carbonic oxide, but, as in the similar reduction of carbonic acid, this reaction is never perfect and some steam always goes through unaltered. The best decomposition is attained in a hot fire, but this is just the condition that is not desirable on account of the formation of clinkers. On the other hand, if the supply of steam be increased indefinitely the fire will

get colder and colder, producing no gas and letting steam and air pass through unconsumed. There is a mean between these extremes which is almost forced upon the operator, wherein the fire is kept at a constant temperature, and in this condition there is not much increase in hydrogen from the steam, while, on the contrary, there is quite a little steam passing away with the gases.



A, ash zone; *B*, combustion zone; *C*, distillation zone; *D*, steam blower; *E*, bearing bar; *F*, grate bar; *H*, hopper; *I*, stoking hole; *K*, neck to gas main; *L*, door for cleaning neck; *M*, damper; *N*, gas main.

FIG. XIII.—THE WELLMAN GAS PRODUCER. VERTICAL SECTION THROUGH CENTER.

In the upper zone of the fire, marked *C* in the drawing, the volatile hydrocarbons of the fuel are distilled by the heat of the combustion beneath, and in this way the gaseous products contain a certain proportion of tarry vapors, some of which are condensed in the conducting tubes. The zones of combustion and distillation are not separated by any arbitrary line, but a goodly share of the rich components of the coal are carried down into the body of the fire and exposed to a high temperature. This causes the separation of carbon, some of which, staying in the fire, is burned with the coal while the rest is carried forward into the conducting tube. When the fire is very hot, large volumes of soot are formed in this way and soon give trouble

in the pipes, but when cool there is little soot but much tar. The worst condition is when holes form in the bed of coal. This allows air to come through and burn the hydrocarbons above the fire with a smoky soot-producing flame, cakes the coal into an unworkable mass, and increases the percentage of carbonic acid in the gas.

The average gas from a Siemens producer is of the following composition:

Siemens Gas.	Per cent. by volume.
CO_2	4.5
C_2H_4	0.4
O	0.4
CO	23.0
H	8.0
CH_4	3.0
N, by difference	60.7
	100.0

It has been shown that some of these percentages, notably of CO_2, H, and CH_4, will vary through wide ranges according to the condition of the fire, but the content of nitrogen will always be about 60 per cent. This component remains passive throughout all the future history of combustion, but it so reduces the calorific intensity that the gas is applicable only to regenerative furnaces.

The ordinary methods of gas analysis fail to take definite account of any save true gaseous components, but in the products of a soft-coal fire there are certain amounts of soot and tar. Some of this material is deposited in the conduits, but this does not constitute a very great part of the total energy. I have elsewhere* recorded that in the case of an exposed 7-foot iron pipe, 250 feet long, the condensation of tar amounted to only three-tenths of one per cent. of the total heat value, while the gas itself, after passing through the tube, contained a proportion that represented from one-tenth to one-eighth of the total heating power.

But although this is the result of theoretical calculations, it is found that when the suspended matters are removed by scrubbing, the value of the gas is reduced very seriously, for it is the tar which gives luminosity to the flame and thereby renders it able to heat not only by direct impact, but by the

The Open-Hearth Process. Trans. A. I. M. E., Vol. XXII, p. 376.

no less potent action of radiation. It is by virtue of this quality that the luminous flames from the dense hydrocarbons so far surpass the clear products of an anthracite fire.

Within the last few years, several different types of producer have been proposed, the main object being the prevention of clinker and the consequent difficulty and expense of cleaning the fire. The most successful way of accomplishing this is by admitting a steam blast through a cone in the center of the fire, thus avoiding all possibility of the air following up the walls. An arrangement of this kind is shown in Figure XIV.

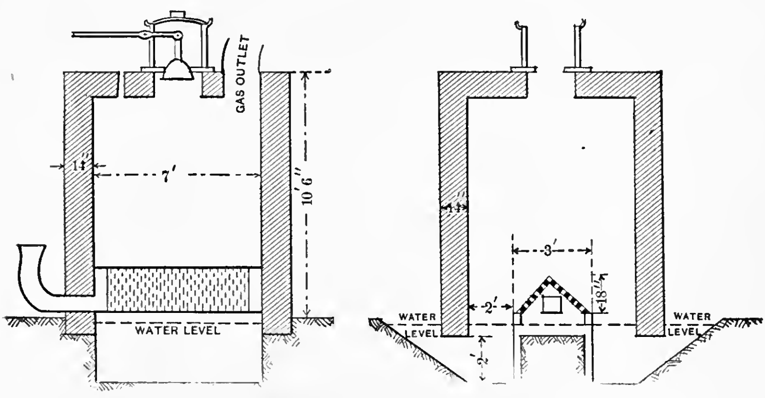


Fig. XIV.—Water-Sealed Gas Producer.

In such producers there is often no grate over a part of the base, but the ash is allowed to accumulate in a thick bed at the bottom. In some cases the producer stands in a pan of water, which serves to cool the ashes, and which also seals the base of the apparatus. By shoveling the ash from beneath the surface of the water, the producer may be cleaned without any interruption of its operation.

CHAPTER X.

THE ACID OPEN-HEARTH PROCESS.

SECTION 68.—*Nature of the charge in a steel-melting furnace.*—In acid open-hearth practice the shell is first lined with nine inches or more of clay brick. The furnace is then heated to nearly the working temperature, and sand is spread in successive layers over the entire hearth. Each layer is heated to a full heat for about ten minutes or until it is "set" so as to be hard, the sand being selected so that it will give as dense and solid a bottom as possible. When finished, the thickness of the lining within the shell should be from 18 to 24 inches.

The area of the cavity for holding the charge will be determined by the size of the furnace, for the depth of the metal should be about 12 to 15 inches in a 5-ton furnace and from 18 to 24 inches when the charge is 30 to 50 tons. If the bath is very shallow, the oxidation is excessive, while if very deep, the rate of melting is slow.

The proportions of the constituents of the charge vary in different places. Sometimes pig-iron alone is used, but when scrap can be obtained it forms part of the mixture. It is always necessary, however, to have a certain amount of pig-iron as a source of supply of the foreign elements, which protect the iron from oxidation. The stock must be of known composition as far as sulphur and phosphorus are concerned, for there is no appreciable elimination of these elements, and the finished product will show a percentage equal to the average of the material charged.

The content of silicon, manganese, and carbon is not limited by such narrow bounds, for these elements are oxidized during the process and their presence in greater or lesser amounts alters the working of the charge rather than the composition of the product. In the manufacture of soft steel it is the

usual practice, when scrap is available, to regulate the proportion of pig-iron so that the melted bath shall be free from silicon and manganese, and shall contain from three-fourths to one per cent. of carbon. During the elimination of this element, the metal is in a state of continual ebullition, and its temperature and condition, as well as the character of the slag, may be completely controlled in preparation for recarburizing and casting.

If too small an amount of pig-iron is used in making up the charge, the molten bath will contain neither silicon, manganese, nor carbon, and will be viscous and pasty. Such a mass will be oxidized by the flame and the oxide of iron will scorify the bottom. At some furnaces it has been the custom to first charge and melt the pig-iron and then add scrap which has previously been heated in a separate furnace, but this practice is expensive and possesses no advantages over the charging of the entire heat at one time.

SEC. 69.—*Chemical history of an acid open-hearth charge during melting.*—The amount of oxidation which takes place during melting is affected by many conditions, being increased by the presence of hydrogen in the gas, by a sharp flame, and by a port construction that allows free air to impinge upon the metal. It is also determined in great measure by the manner in which the stock is charged. The pig-iron should be spread as evenly as possible over the scrap, so that it will melt first and trickle over the hot steel, and thus each atom of iron will be protected by the contiguity of an atom of silicon or carbon for which the oxygen has a greater affinity.

Practically it is impossible to obtain perfect protection, and when only a small proportion of pig is used there will be spots where the scrap is entirely uncovered, and in these places large amounts of iron oxide will be produced. If this cinder forms a pool on the viscous surface of the charge, it will be mixed sooner or later with high-carbon metal, and an interchange will occur with reduction of iron, the result being the same as if mixture had taken place at an earlier stage. But if the fused oxide comes in contact with the hearth, scorification will ensue with formation of silicate of iron, and though at a later period this scoria may be mixed with high-carbon metal, the harm can not be completely remedied. A portion

of the iron may, perhaps, be reduced and a higher silicate be formed, but silica once having entered the slag is there to stay, and will permanently hold a greater or less amount of iron oxide.

The value of the elements found in pig-iron in protecting the scrap from oxidation will be in proportion to their ability to unite with oxygen. Calculating this we have the following table:

1 unit of carbon combines with 1.333 units of oxygen to form CO.
1 unit of silicon combines with 1.143 units of oxygen to form SiO_2.
1 unit of manganese combines with 0.291 units of oxygen to form MnO.
1 unit of titanium combines with 0.176 units of oxygen to form TiO_2.

This table represents a very broad truth, but it must not be translated too literally, for some elements are preferable to others. It is necessary that after melting the metal should be protected from the flame by a layer of slag containing about 50 per cent. of silica. If the charge is made up of one quarter pig-iron carrying one per cent. silicon, the silica produced by oxidation, the sand attached to the pig-iron, and the material derived from the scouring of the hearth, are usually sufficient for the requirements of the cinder, but with very low-silicon pig-iron, free from adhering sand, it may be necessary to add additional silica to prevent the basic slag from making inroads upon the bottom. On the contrary, if the

TABLE 33.

Elimination of Metalloids in an Open-Hearth Charge.

Nature of Sample.		Group I.	Group II.
Pig-iron, pounds		11,700	20,700
Steel scrap, pounds		45,550	36,800
Composition of original charge, per cent. (estimated)	Si	0.40	0.65
	Mn	0.90	0.85
	C	1.00	1.50
Metal when melted, per cent.	Si	.02	.05
	Mn	.09	.06
	C	.54	.64
Slag after melting, per cent.	SiO_2	50.24	49.46
	MnO	21.67	13.16
	FeO	23.91	33.27

silicon in the pig-iron is very high, the slag will be viscous and infusible. The presence of manganese helps to counteract this viscosity, but in the absence of this element iron oxide must be added in the shape of ore, or formed from the bath by waste of iron.

The way in which the metalloids are eliminated during the melting will be best understood from the typical records given in Table 33. Each column represents the average of a group of consecutive charges; Group I includes nineteen heats melted with soft-coal producer gas, and Group II six heats made with oil vapor.

It will be seen that the oil vapor is much more oxidizing than the coal gas, so that although the original charge was very much higher in oxygen-absorbing elements, the bath after melting had about the same composition in both cases. The slag shows a great variation in the oxides of iron and manganese; this arises from the fact that the amount of manganese was limited by the content in the charge, and since the slag required a certain proportion of bases, the deficit was made up by oxidation of iron.

Sec. 70.—*Chemical history of an acid open-hearth charge after melting.*—After the melting it is necessary to oxidize the remaining carbon, manganese, and silicon, by keeping the bath at a high heat and adding iron ore in successive doses, thus forming silica and oxide of manganese which go into the slag, and carbonic oxide which escapes with the flame. This combustion of carbon produces a bubbling over the entire surface of the bath, continually exposing the metal to the flame, and aiding materially in keeping it at a high temperature. The union of the oxygen of the ore with the silicon and carbon sets free metallic iron which is immediately dissolved by the bath.

If the ore is added properly, it is reduced as fast as it is put in, as will be evident from Table 34, which shows the history of the metal and the slag in the groups above considered. In Group I an average of 1020 pounds of ore was used on each heat to decarburize, while on Group II only 850 pounds was added. It will be seen that in spite of the addition of the ore the character of the slag remains unchanged. There is an increase of FeO, but this does not show an increase in basicity, for the volume of slag is increasing throughout the operation both from the wear of the hearth and the silica from the ore, so that in order that the composition of the slag should remain absolutely the same it would be necessary that there be a simultaneous supply of exactly the right proportions of

both MnO and FeO. It is evident that this can not happen, for the metal after melting is nearly free from manganese, and since the ore contains none there is no source of supply of this element. With the dilution of the slag, therefore, there is a vacancy left for a base, and iron oxide is the only available candidate. That this is the true explanation will be seen from the totals of MnO and FeO, which show that the slag at the end of the operation is almost identical with the slag after melting, since the sum of these factors represents the real basicity of the cinder.

TABLE 34.

History of Metal and Slag in an Acid Open-Hearth Furnace.

Subject.		Composition, per cent.			
		Group I.		Group II.	
		After melting.	End of operation.	After melting.	End of operation.
Metal.	Si	.02	.02	.05	.01
	Mn	.09	.04	.06	.02
	C.	.54	.13	.64	.12
Slag.	SiO_2	50.24	49.40	49.46	49.36
	MnO	21.67	16.50	13.16	11.30
	FeO	23.91	29.79	33.27	34.11
	MnO + FeO . .	45.58	46.29	46.43	45.41

SEC. 71.—*Quantitative calculations on acid open-hearth slags.*—The foregoing results are purely qualitative, and they do not show the alteration in the amount of the slag which takes place during the progress of the operation. It will be evident that it is out of the question to actually weigh the cinder at different periods, but, nevertheless, it is possible to approach the truth by the following method: The final slag, after tapping, is weighed when cold. By subtracting from this weight the MnO produced by the addition of the recarburizer and the sand derived from the taphole and ladle-linings, the amount of slag which was in the furnace before tapping may be computed. Given the analysis of the slag at that time, it is easy to calculate the weight of its various constituents, among which will be the manganese; if the ore contained no appreciable quantity of this element, the amount which in one form or another was present throughout the operation will be known; and since the percentage of manganese in the slag and in the metal can be determined by analysis, and the

weight of the metal can be calculated for any stage of the work, all the requisite data are at hand for a determination of the weight of the slag at any time. With this determination as a basis, the quantitative estimation of the factors is a matter of simple arithmetic.

This process applied to the two groups of heats in Table 34 gives the results shown in Table 35. This shows that although nearly twice as much pig-iron was added in Group II, as recorded in Table 33, the greater oxidizing power of the oil flame took care of this extra amount, the result being plainly seen in the greater quantity of slag which was present after melting. When the bath was thoroughly fluid, the oil flame still acted more powerfully, but it was unable to burn any of the iron since the metalloids furnished ample protection, and the increase in the weight of slag during oreing is no greater in the one group than in the other. In Group I, 41 per cent. of the

TABLE 35.

Calculation on the Weight of Certain Open-Hearth Slags Mentioned in Table 34 and the Amount of FeO Reduced During Oreing.

Subject.	Group I.	Group II.
	Coal gas, pounds.	Oil gas, pounds.
Slag after tapping	4050	5670
Slag after melting	2810	4530
Ore added	1020	850
FeO in ore added	643	536
FeO reduced during oreing	336	313

ore was reduced, while in Group II there was 45 per cent. These figures have no general significance, for, if the slag is slightly viscous after melting, a certain amount of ore will be necessary to confer fluidity and will not be reduced. Since this quantity will be a constant under given conditions no matter how much ore is afterward needed, it will be evident that it might be 90 per cent. of a small addition and only 10 per cent. of a large one.

SEC. 72.—*Reduction of iron ore when added to an acid open-hearth charge.*—This reduction of ore is a matter of vital importance in using large proportions of pig-iron. Quite an amount of oxide is then necessary to satisfy the silicon of the pig as well as the sand adhering to it, but after the slag is

formed there is no increase in its volume except from the impurities in the ore and the wear of the hearth, so that as fast as the ore is added its oxygen is transferred to the metalloids and its iron to the bath. This may be illustrated by Table 36, which gives the records of heats which are not included in the tables just given, on each of which 1500 pounds of ore were added after melting to decarburize the metal.

Table 36.

Data on Open-Hearth Slag and Metal at Different Periods of the Operation.

Composition of the Slag.

Pounds of ore added.	Constituents, after addition of ore as shown in first column.	Number of Heat.				
		7596	7598	7606	7635	Average
None.	SiO_2, per cent.	50.27	51.96	52.43	52.94	51.90
500	" "	49.27	51.10	55.82	51.72	51.98
1000	" "	52.77	50.30	55.73	52.28	52.77
1500	" "	50.97	51.48	55.66	52.90	52.75
None.	MnO, per cent.	14.91	21.65	15.61	21.84	18.50
500	" "	15.20	19.09	15.31	20.44	17.51
1000	" "	14.70	17.50	13.89	19.06	16.29
1500	" "	14.22	16.72	12.40	16.36	14.92
None.	FeO, per cent.	31.23	22.59	27.14	23.18	26.03
500	" "	30.68	26.12	25.11	24.21	26.53
1000	" "	26.96	28.26	26.20	26.26	26.92
1500	" "	31.70	26.03	26.96	29.13	28.45
None.	FeO and MnO, per cent.	46.14	44.24	42.75	45.02	44.54
500	" "	45.88	45.21	40.42	44.65	44.04
1000	" "	41.66	45.76	40.09	45.32	43.21
1500	" "	45.92	42.75	39.36	45.49	43.38

Composition of the Metal.

Heat No.	Silicon, per cent. After adding ore, as below.				Manganese, per cent. After adding ore, as below.			
	None.	500 lbs.	1000 lbs.	1500 lbs.	None.	500 lbs.	1000 lbs.	1500 lbs.
7596	.07	.01	.01	.01	.10	.02	.02	.02
7598	.04	undet.	undet.	.01	.02	.02	.02	.02
7606	.04	.05	.03	.02	.08	.05	.03	trace.
7635	.13	.07	.05	.06	.19	.08	.09	.10

Samples were taken of metal and slag after every 500 pounds of ore. These groups and heats were not selected to show this special action, the investigation being made for other purposes; but the wonderful regularity in results, corroborated as it is by many other records, shows that in the magnificent alembic of the melting furnace, at the highest heat we know save that of the electric arc, at a temperature when wrought-iron melts like wax in the candle flame, the molecular relations are guided by fixed and unalterable laws.

It is this stability of conditions that gives to the open-hearth melter the ground on which he can work out regular and reliable results, and which makes the process peculiarly fitted for the manufacture of structural material.

Sec. 73.—*Pig-and-ore process.*—The amount of ore required for a charge will not follow closely the amount of carbon, since the flame is constantly at work, and ore is added when the melter thinks it advisable rather than when it is absolutely necessary. If the charge is hot it dissolves the ore rapidly and there is little chance for the flame to do its share of oxidation, while if the charge is cold only a small amount of ore will be added and the oxygen will be derived from the gases. Thus any attempt to make an arbitrary equation of the action must fail, but it may be broadly said that if the bath contains one per cent. of carbon, 1500 pounds of ore may be used in bringing it down to .08 per cent. The first 500 pounds will reduce it to about .80 per cent. of carbon, the second to .40 per cent. and the third will finish the work. If silicon and manganese should be as low during the interval between the first and second ore additions as at a later time, the burning of the carbon might be the same then as later, but either the presence of these protectors or the less favorable physical condition of the slag in a high-carbon bath retards the action at the start. When large quantities of high-silicon or high-manganese pig-iron are used, the first additions of ore are consumed by the unburned excess of these elements, and hundreds and even thousands of pounds of ore may be added after melting before the carbon is affected. Therefore, when it is necessary to charge nothing but pig-iron, it is advisable to have it contain as little silicon as possible, and even then the oxidation of carbon requires several hours. The ore is not lost, for the reduced iron makes up for the metalloids which are burned, so that the weight of the steel will nearly equal the weight of the pig-iron charged.

The expense of the pig-and-ore process rests in the slow combustion of carbon, for it is impossible to hurry the work without causing violent boiling of the voluminous slag, producing scorification of the hearth and possibly a loss of metal through the doors. Since the fuel consumption per hour is nearly the same during the period of oreing as it is during

the period of melting, it is plain that there is a considerable decrease in product with an increased fuel ratio. By the use of a tilting furnace this difficulty may be lessened, for as soon as the silicon has been oxidized, the contents of the furnace may be emptied into the ladle and then the metal be immediately returned to the furnace with as little slag as desired. When most of the slag is thus removed, the action is much more rapid and there is no trouble from frothing. The tapping of slag from stationary hearths has always resulted unsatisfactorily, and the same is true of attempts to remove it from a tilting furnace by surface decantation, but this process of repouring requires no handling save the raising of the ladle in a vertical line so as to allow the metal to be returned to the furnace through the same hole from which it has just been tapped, and seems to solve the question of slag removal in a simple way.

SEC. 74.—*Conditions modifying the character of the product.* —If the temperature of the metal is very high, the last traces of silicon will not be oxidized, for the affinity of silicon for oxygen is a function of the temperature. In the Bessemer converter the metal may contain as much as one per cent. of silicon if blown sufficiently hot, but in the open-hearth there is no chance for the bath to arrive at an intense degree of heat as long as a considerable percentage of this element is present; for superheating is not readily attained without a lively bath, and the bath will very seldom be lively as long as it holds a high content of silicon. Thus the open-hearth can not rival the converter in producing high-silicon metal by non-combustion, but under suitable conditions the amount carried along in the metal may be quite appreciable, and, by holding the bath at a very high temperature with a silicious slag, there will even be a reduction of the silica of the hearth according to the equation

$$SiO_2 + 2C = Si + 2CO.$$

This variation in affinity of Si for O plays an important part in the production of steel castings where a higher temperature is used than for ingots of ordinary size. The constant presence of a small proportion of silicon, due to the high temperature, tends to prevent the absorption of

gases, and it is stated by Odelstjerna* that if at any time the metal is allowed to cool so that the last traces of silicon are burned, the gases which are absorbed can not be expelled by a subsequent superheating.

I am of the opinion that Odelstjerna is correct in his statements, but that there may be other factors involved in a full explanation. It is certain that in the manufacture of small ingots which are to be rolled directly into plates, there are delicate adjustments of temperature and slag that are not easily explained by considering the history of silicon alone.

One of these factors, which may be cited by way of illustration, is the extent and force of the oxidizing influence. It is the opinion of some metallurgists that the best quality of open-hearth steel can only be made when the burning of the metalloids is carried on at a very slow rate, so that the bath shall not contain an excess of oxygen at any time, and it is stated by Ehrenwerth† that a certain American works makes a practice of keeping a charge in the furnace a very long time when a very good quality of steel is desired. As a matter of fact, the works in question did carry out such a system at one time out of respect to foreign tradition, but found no advantage in so doing, and has long since discontinued the practice.

It is also an opinion, held by men of acknowledged reputation, that a high proportion of pig-iron in the original charge will give a superior product. If this is true, it probably arises from the fact that the presence of a high proportion of carbon after melting, with the consequent long exposure to the flame, will result in a thorough washing of the bath. I believe that there is a limit to this action, and that very little can be gained by raising the content of carbon in the melted bath above one per cent., for this proportion insures a vigorous boil.

It is difficult to see how the condition of the bath, after it has been run down from one per cent. of carbon to three-tenths of one per cent., can be any different from the condition which would have existed if the original content had been two per cent. It would seem probable that one or two hours of exposure of the

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* *Trans. A. I. M. E.*, Vol. XXIV, p. 308.

† *Das Berg- und Hüttenwesen auf der Weltausstellung in Chicago.* Ehrenwerth, 1895, p. 276.

completely liquid bath to the flame would give ample opportunity for any reactions which could be in progress, and the old adage that "enough is as good as a feast" might be applied to the present case. It is not unprofitable, however, to consider the conclusions from practical experience, however invalid they may appear, for they may sometimes represent a vital truth, albeit our point of view may not be high enough to allow a complete survey of the field.

SEC. 75.—*History of sulphur and phosphorus.*—In the above records no account is taken of sulphur or phosphorus, but numerous determinations and universal experience prove that the content of phosphorus in the steel will be determined by the initial content in the charge. It is true that acid open-hearth slag may contain some phosphorus, and I have found one case where it held 0.04 per cent., but it would require a higher percentage than this to make a difference in the metal that could be detected by ordinary analysis, so that for practical purposes it must be assumed that every molecule of phosphorus that is present in the pig-iron, scrap, and ore, will appear in the finished metal.

The percentage of sulphur can not be predicted with so much precision. Traces of this element may be burned during melting and pass away as sulphurous anhydride, but the proportion thus eliminated is small. On the other hand, there is a tendency to absorb sulphur from the flame. With fairly good coal this increment may be neglected, but with bad coal, and especially when the slow working of the furnace renders it necessary to expose the charge to the gases for a long time, the amount thus absorbed may be ruinous. It has been suggested with some reason that the presence of lime in the coal might retain at least a part of the sulphur in the ashes of the producer, so that it would not appear in the gas. The ore is another source of contamination, for it generally contains a certain proportion of pyrites. As the ore floats on the surface of the bath, some sulphur may be oxidized above the surface and the products pass away with the flame, but the remainder will be absorbed by the bath.

SEC. 76.—*Method of taking tests.*—The condition and nature of the metal and slag are determined from time to time by taking samples from the furnace by means of a small ladle and

casting test-ingots with a cross-section about one inch square. These are chilled in water and broken, and the carbon is estimated from the appearance of the fracture. The reliability of such a determination depends upon the constancy of the conditions of casting and chilling, and the expertness of the judge, but, roughly speaking, the content can be ascertained within 10 per cent. of the true amount.

SEC. 77.—*Recarburization.*—When the desired point has been reached the recarburizer is added, this being almost invariably used in a solid state. It is generally heated red hot, but this is not essential, for, in making structural steel, "ferro" containing 80 per cent. of manganese is used almost exclusively, and the weight of the addition is so small that it chills the bath only slightly. The ferro may be added to the metal while in the furnace, and this method has the advantage that the bath can be thoroughly stirred after the recarburizer has melted, but it has the disadvantage that during the time the last pieces are fusing, the portions which melted first are losing their manganese to the oxygen of the slag and flame. In a hot furnace this action is very rapid, and although the entire addition may melt in less than a minute, a considerable proportion of manganese is lost by oxidation.

When the recarburizer is added in the ladle, it is evident that the latter action will not occur, but there will be a certain loss on account of the oxide of iron contained in the metal, and which it is the function of the recarburizer to remove. This loss will be the same whether the addition is made in the furnace or in the ladle; but the effects of slag and flame are absent. Hence it follows, all other things being equal, that the loss will be more regular when recarburization is performed in the ladle, and this is equivalent to saying that the content of manganese in the steel can be made more nearly alike throughout a series of heats.

The amount of manganese lost in recarburization not only varies with the way in which it is added, but also with the carbon of the bath and with the percentage of manganese put in. As would naturally be supposed, the amount of oxide in the bath is less with high than with low carbons, and so the loss in recarburizing decreases as higher steel is made. It is also found that the loss is less with smaller percentages of manga-

nese, so that with the same bath, if 1.00 per cent. of Mn be added, there will be .60 per cent. in the metal, being a loss of .40 per cent., while if .60 per cent. be added the steel will have .40 per cent., being a loss of only .20 per cent. It seems as if with the lower manganese the action was not perfect, and that with each successive increment of ferro an additional atom of oxygen is removed. This fact holds good whether the recarburizer is added in the furnace or in the ladle.

The fear of non-homogeneity under the practice of adding the ferro in the ladle is not entirely unfounded when small heats are made and the metal is not very hot. But when charges of 20 to 50 tons of hot steel are properly poured and recarburized, the steel is thoroughly uniform. When metal is made very high in manganese, certain precautions must be taken, but in ordinary structural steels, when the manganese runs below .65 per cent., there is an all-pervading action throughout the melted mass which dispels all thought of non-homogeneity.

SEC. 78.—*Advantages of the open-hearth process in securing homogeneity.*—In the low steel of the Bessemer process there is very little trouble from irregular distribution, although the more viscous slag sometimes holds pieces of the solid recarburizer and keeps them from melting until the steel is nearly all poured. The result is that when they do finally fuse, small streams of high manganese metal flow down into the upper part of the last ingot and form a hard spot in the steel. This does not and should not often happen, and most Bessemer soft steel is uniform throughout. In making high-carbon steel, however, the conditions of manufacture make the hearth far superior to the converter. The metal in the Bessemer process is always blown until nearly all the carbon is eliminated, since it has been found impracticable to stop the operation at any definite intermediate point. All the carbon content of the steel, therefore, must be added in the recarburizer, and absolutely perfect homogeneity can only be secured by absolutely perfect mixing. In the open-hearth, on the other hand, high-carbon steels are made by interrupting the process at the desired stage, and it is plain that no mixing is required as far as carbon is concerned, and about the same quantity of recarburizer will be used for a given manganese whether high or low steel is being made.

CHAPTER XI.

THE BASIC OPEN-HEARTH PROCESS.

SECTION 79.—*Construction of a basic open-hearth bottom.*—The basic process, as herein discussed, consists in melting a charge of pig-iron, or a mixture of pig-iron and low-carbon metal, upon a hearth of dolomite, lime, magnesite, or other basic or passive material, and converting it into steel in the presence of a stable basic slag by the action of the flame, with or without the use of ore, and by the addition of the proper recarburizers, the operation being so conducted that the product is cast in a fluid state.

In the above specification that the slag shall be stable, no recognition is accorded that hybrid practice wherein a little lime is thrown into an acid furnace, near the end of the operation, with the intention of removing a part of the phosphorus by the temporary and uncertain action of a partially basic slag. Regular metallurgical results can only be obtained under regular conditions, and to this end the hearth should be made of material that will not be scorified by basic additions. The current belief that the lining of the bottom is the dephosphorizing agent is a complete mistake, for the highest function of the hearth is to remain unaffected and allow the components of the charge to work out their own destiny. In practice it is never possible to construct either an acid or a basic bottom so that it is entirely passive, for a slag which is viscous with silica will slowly attack a pure sand bottom, and a cinder which is mucilaginous with lime will gradually eat into a dolomite hearth.

For the construction of a permanent bottom, carbon, bauxite, lime, chromite, magnesite, and dolomite, have been used. Magnesite gives the best results but it is very costly,

and well-burned dolomitic limestone answers well enough. In some places the stone is used in its natural state, but this is a doubtful economy, the better plan being to thoroughly roast it in special kilns and then grind and mix with tar. The roof and walls being made of silica bricks, it is necessary to have a joint of chromite or other passive material between the acid and the basic work; but it must be understood that at the intense heat of a melting furnace, and in an atmosphere charged with spray of iron oxide, almost any two substances will unite if pressed together, so that the part of the joint which bears the weight of the superposed brickwork must be shielded from the direct action of the flame.

SEC. 80.—*Functions of the basic additions.*—Given a hearth capable of resisting the action of metal and slag, the problem of the basic furnace is the melting and decarburization of iron as in acid practice, with the additional duty of removing a reasonable quantity of phosphorus and some sulphur. Under the oxidizing influence of the flame and ore, the phosphorus is converted into phosphoric acid (P_2O_5) which can unite with iron oxide, but the conjunction will be only temporary, for the carbon of the bath reduces the iron, leaving the acid helpless, and then the phosphorus in its turn is robbed of its oxygen and returned to the bath. But if lime is added, the acid can form phosphate of calcium, and since the oxide of this element can not be reduced by the carbonic oxide, the phosphorus is never left without a partner, but forms part of a stable cinder.

This oxide of calcium is sometimes added in the form of common limestone, the carbonic acid being expelled in the furnace. It will be evident that this entails a considerable absorption of heat, and the melting must be delayed accordingly, but it has a compensating advantage in that the gas, in bubbling through the metal, keeps up a motion which facilitates chemical action, and also that the carbonic acid gives up part of its oxygen to the silicon, phosphorus, carbon, and iron.

This oxidizing action allows the use of a greater proportion of pig-iron, and also aids in the removal of phosphorus, so that there seems to be good ground for using the cheap natural stone. It is believed, however, to be more economical to put it through a preliminary roasting and reduce by nearly 50 per

cent. the amount of basic addition, for the rate of melting is thereby hastened, while the oxidizing effect can be obtained by the use of ore. It is true that ore costs more than stone, but, on the other hand, its full value is returned in metallic iron, and, moreover, it is possible to use a greater proportion of pig-iron on account of the reduced quantity of gas evolved, for the amount of oxidation done during melting, either by stone or ore, is limited by the frothing of the stock, and this is evidently determined by the amount of gas evolved in the reactions. Therefore, if ore produces less gas than stone in oxidizing a given quantity of carbon, then more pig can be used with ore than with stone. The reactions are as follows:

Limestone, $CaCO_3 + C = 2\,CO + CaO$.
Ore, $Fe_2O_3 + 3C = 3CO + 2\,Fe$.

Thus two volumes of gas are formed for each atom of carbon when stone is used, while only one volume is produced with ore.

The available oxygen in the ore is nearly twice as much as in the same weight of stone, so that by using a mixture of 500 pounds of burned lime and 500 pounds of ore, there will be the same quantity of basic earth, and the same oxidizing effect, as with 1000 pounds of raw stone, while there will be only half as much gas produced with a contribution of 300 pounds of metallic iron, and much less refrigerating effect.

Sec. 81.—*Use of ore mixed with the initial charge.*—This ore and lime is put into the furnace with the pig and scrap, so that the hearth will be protected during the melting and an active cinder be at work continuously. When high-phosphorus stock is used, the amount of oxidation to be done for a given weight of pig-iron is much greater than in acid practice. Thus in 10,000 pounds of low-phosphorus iron for an acid open-hearth, the oxygen-absorbing power is as follows:

1.0 per cent. silicon = 100 pounds Si, absorbing	114.3 pounds oxygen.
3.5 per cent. carbon = 350 pounds C, absorbing	466.7 pounds oxygen.
Total oxygen absorption,	581.0 pounds.

If pig-iron be used in basic work with the same content of silicon and carbon, but with the addition of 1.00 per cent. of phosphorus, there will be an additional absorptive power of 129 pounds of oxygen or a total of 710 pounds. If the first mixture were put

into a furnace there would be about 40 per cent. of the work done during the melting (under the conditions shown in the preceding chapter), so after melting there would remain 60 per cent. of 581, or 349 pounds of oxygen to be given to the bath. In the second case, it is evident that the presence of phosphorus will not cause a greater action during melting, but that if all other conditions are similar, the total absorption will be the same, so that, after melting, the phosphoritic bath will have an absorptive power of $349 + 129 = 478$ pounds of oxygen, and there will be one-third more work to do during the period of oreing with the same proportion of pig.

These figures may seem somewhat abstruse, but they explain the very important fact that there is much more oxidation to do with phosphoritic iron than with good stock, so that it is advisable to use ore mixed with the charge to perform a part of the work during fusion. On an acid hearth, when running exclusively on pig-iron, ore is sometimes added with the original charge, but there is always danger of this oxide uniting with the sand of the hearth before the metalloids can reduce it. In basic practice, on the contrary, the ore can do no harm, for it has little effect on the dolomite and soon reacts upon the silicon, phosphorus, and carbon.

TABLE 37.

Average Composition of Slag and Metal from Seventeen Basic Heats.

Test.	Metal. Composition, per cent.				Slag. Composition, per cent.					
	C.	Si.	Mn.	P.	SiO_2.	MnO.	CaO.	MgO.	FeO.	P_2O_5
A	.71	.06	.33	.046	19.21	11.12	42.16	6.64	13.68	5.149
B	.34	.01	.25	.022	16.37	10.36	42.78	7.87	16.29	4.848
C	.12	.01	.22	.013	15.08	9.01	42.16	8.45	20.34	3.850
D	.16	.01	.49	.018	15.75	14.11	39.05	10.40	16.65	2.961

SEC. 82.—*Chemical history of basic open-hearth charges when no ore is mixed with the stock.*—The addition of ore is not necessary when sufficient scrap is available, for the flame will supply oxygen to the metalloids, as will be shown by Table 37, which gives the average history of 17 heats when no ore was used with the original charge, and when tests of metal and slag were taken at four different epochs. The heats were all similar in character and were operated under similar condi-

tions, and therefore the mixing of slags and metals to obtain average results is justifiable. Each charge was made up of about one-half pig-iron and one-half steel scrap, and contained 2.00 per cent. carbon, 0.40 per cent. silicon, 0.85 per cent. manganese, and 0.20 phosphorus. Tests of slag and metal were taken as follows:

(*A*) After complete fusion of metal without ore.

(*B*) At beginning of boil, after the addition of 1965 pounds of ore per heat.

(*C*) When the bath was ready for the recarburizer, 775 pounds of ore being added per heat between tests *B* and *C*.

(*D*) After casting.

Sec. 83.—*Elimination of phosphorus during melting.*—The elimination of phosphorus during melting is a variable, depending upon the conditions of oxidation and the ability of the slag to absorb the phosphoric acid. Table 38 will show in a general way the proportions of carbon and phosphorus that are oxidized during melting under different kinds of practice.

TABLE 38.

Elimination of Phosphorus and Carbon During Melting upon a Basic Hearth.

Group.	Pounds of ore charged with stock, per ton of metal.	Number of heats in group.	Composition of metal, per cent.						Composition of slag after melting; per cent.	
			Phosphorus.			Carbon.				
			Initial.	After melting.	Per cent. eliminated.	Initial.	After melting.	Per cent. eliminated.	SiO_2.	FeO.
1	none.	17	0.20	.046	77	2.00	.71	65	19.21	13.68
2	none.	4	1.36	.594	57	1.50	.60	60	14.90	und.
3	none.	9	0.19	.023	88	1.80	.27	85	15.55	19.68
4	none.	9	0.19	.072	62	1.80	.78	57	19.98	12.20
5	300	3	2.50	.744	70	3.50	.59	83	11.96	8.61
6	115	6	0.55	.274	50	2.90	1.00	66	30.73	10.71
7	140	7	0.55	.402	27	2.90	1.48	49	34.22	10.95

Sec. 84.—*Composition of the slag after melting.*—Neither the percentage nor the total amount of elimination during melting is a matter of vital importance, for whatever work is left undone during that period will be completed before tapping. In this removal of phosphorus after fusion, the composition of the slag is the important factor, and this will depend, primarily, upon the amount of silica, and, secondly, upon the lime added. The total supply of silica will deter-

mine the quantity of lime, and it will also determine the weight of the resultant cinder. Thus, if the final slag is to contain 16.67 per cent. of SiO_2 and 50 per cent. CaO, it is evident that the basic additions must contain $\frac{50.00}{16.67}$ = three times as much available CaO as there is SiO_2 in the entire charge, and also that the final slag will weigh six times as much.

The composition of the cinder differs considerably, for when good stock is used it may contain over 20 per cent. of silica and still be capable of eliminating the impurities, but when much phosphorus is to be removed, the silica must sometimes be as low as 12 per cent., the proportion of CaO usually varying inversely with the silica. The amount of lime which can be taken up is limited, for at a certain point the slag becomes viscous, particularly when the scorification of the hearth supplies magnesia. Allowing for about 10 per cent. of MnO, 8 per cent. MgO, 18 per cent. FeO, and 4 per cent. Al_2O_3, etc., it may be roughly stated that with 12 per cent. of SiO_2 there will be about 48 per cent. CaO, while with 20 per cent. of SiO_2 there will be 40 per cent. CaO. In the attainment of this ratio between SiO_2 and CaO the purity of the lime is an important factor, especially when a slag low in silica is needed. Ordinary lime as it comes from the kiln contains a certain unexpelled percentage of CO_2, and, in the handling and exposure prior to use, it absorbs a certain amount of moisture, so that with the usual proportions of earthy impurities it will average about 80 per cent. of CaO.

SEC. 85.—*Relative value of limes as determined by their chemical composition.*—The content of SiO_2 in the lime depends entirely upon the kind of stone used and the care with which the ash of the fuel is kept separate. When a choice must be made between a cheap and impure lime and a more costly article low in silica, the value of each may be calculated by finding the excess of CaO over what is necessary to satisfy its own acids. Two representative limes are assumed in Table 39, both containing 80 per cent. CaO, one with 3 per cent. and the other with 7 per cent. SiO_2, and the computation is made for two different slags.

It will be seen that the pure lime is worth 31 per cent. more than the impure kind when a calcareous slag is to be

formed, but if a more silicious cinder is permissible, as in the case when very little phosphorus is to be removed, the pure lime is worth only 12 per cent. more.

TABLE 39.

Relative Values of Limes with 3.0 and 7.0 per cent. of SiO_2.

	Slag A.		Slag B.	
	Lime with 3 per cent. SiO_2.	Lime with 7 per cent. SiO_2.	Lime with 3 per cent. SiO_2.	Lime with 7 per cent. SiO_2.
SiO_2 in slag; per cent.	12.0	12.0	20.0	20.0
CaO in slag; per cent.	48.0	48.0	40.0	40.0
Ratio CaO to SiO_2 in slag	4.0	4.0	2.0	2.0
Total CaO in lime; per cent.	80.0	80.0	80.0	80.0
CaO in the lime which is needed to satisfy its own silica; per cent.				
4.0×3.0	12.0	......	......	......
4.0×7.0	......	28.0	......	......
2.0×3.0	......	......	6.0	......
2.0×7.0	......	......	......	14.0
CaO available for foreign silica; per cent	68.0	52.0	74.0	66.0
Relative value.	1.31	1.00	1.12	1.00

SEC. 86.—*History of basic open-hearth slags.*—The proportions of SiO_2 and CaO are the main points in the construction of a basic slag, but there are other factors which exercise an important influence upon the result. Magnesia is always present from the wear of the hearth, but is rather undesirable as it makes the slag viscous and has much less power to hold phosphorus than lime. Alumina comes from the impurities in the dolomite, lime, and ore, but being usually in small amount may be neglected except when an analysis is expected to add up to 100 per cent. The same is true of the alkalies and small percentages of miscellaneous impurities. Manganese is usually present in the stock and serves a useful purpose in conferring fluidity upon the slag, so that, being a base itself, the total basic content can be higher than with a slag containing only silica and lime. It is also valuable in removing sulphur, for there is a tendency toward the formation of sulphide of manganese, which floats to the top of the metal where the sulphur, being exposed to the flame, is oxidized and passes away with the waste gases. This action is rather uncertain, and, in fact, the explanation is somewhat a matter of supposition, but it seems quite well proven that manganese, either

metallic or in the form of ore, aids in the elimination of sulphur, and the above theory is in accord with certain well-known phenomena of liquation in the purification of pig-iron by the addition of spiegel, as described by Massenez.*

All the components thus far enumerated are in great measure fixed and determined agents in the transactions. It is true that manganese is sometimes reduced from the slag by the carbon of the bath, and also that a certain percentage may remain unoxidized in the metal, but aside from this it may be said that the oxides of aluminum, silicon, and manganese exist in the slag in just the quantities that were added with the stock; but there are three other constituents, iron oxide, phosphoric acid, and sulphur, whose presence in the slag is determined by the conditions of manipulation and by the proportions of the other constituents.

Iron oxide is always present in greater or less extent, the exact amount depending upon the reducing power of the carbon of the bath. It matters not whether ore is added before melting, after melting, or not at all; there is a certain content of FeO which is demanded by the existing conditions, and that certain content will be present. An exception must be made in the case of ore added after the carbon is nearly eliminated, but aside from this there will be just as much iron oxide lost in the slag when no ore is used as when it has been added in proper quantity, and therefore it may be assumed that all the ore is a clear gain and that its iron is all reduced and added to the metallic bath.

The presence of iron oxide in either acid or basic slag is an anomaly, for in an ordinary acid charge it seems as if the oxidation of the silicon and manganese would be sufficient to produce a slag without other aid. Nevertheless we have found in the foregoing chapter that there is a force at work in an acid furnace which is constantly creating a slag with a composition of about 50 per cent. SiO_2 and 45 per cent. FeO + MnO. If more FeO is added, the carbon of the metal immediately seizes the oxygen and sets free metallic iron, but the same powerful action which so quickly accomplishes the

* *On the Elimination of Sulphur from Pig-Iron. Journal I. and S. I.*, Vol. II, 1891, p. 76.

destruction of this excess is not able to pass much below the limit even by exposure for hours without any addition of ore. There is an automatic adjustment to a fixed status which is one of the most wonderful phenomena of chemical physics. The only explanation I can offer is that it is an instance of the general law that all forces tend to work along the lines of least resistance, which, being interpreted for this case, means that a slag will seek to combine with anything that promotes fusibility. If given the opportunity a silicious slag absorbs either bases or silica, but preferably bases, and particularly those which impart the greatest fluidity. This action tends to continue indefinitely, and in an acid furnace, if the heat is not tapped after the carbon is burned, the formation of iron oxide will go on with great rapidity, and the fluidity of the slag will be greatly increased in spite of the cutting of the hearth. This latter action is a correcting condition, but it is not the controlling influence under ordinary circumstances, as is proven by the small amount of the scorification of the hearth during oreing. The real determinant is the carbon of the bath, and there is an equilibrium established between the oxidizing power of the flame, the reducing power of the metalloids, and the struggle after fluidity.

In the basic process there is a difficulty in making a slag composed entirely of silicate of lime, for this is much more viscous than a slag of the same percentage of silica containing other bases; there is a tendency, therefore, toward the absorption of iron oxide, but this is opposed by a contest on the part of the lime for the possession of the silica, and the result is a decrease in the percentage of iron when there is an increase in lime. Inasmuch as the substitution of CaO for FeO produces a more viscous slag, this would seem to invalidate the theory just advanced, but, as above indicated, the effect is due not to a change in the law but to the action of stronger forces. The more bases that are present, the less necessity is there for an additional amount, since the weight of silica necessarily remains constant, and, as the reducing action of the metalloids comes into play, the slag begins to be robbed of its iron, which at the same time is its most reducible and its most fusible base. The presence of oxide of manganese in the slag modifies without completely changing the

relations just described, for, by furnishing an additional base and imparting greater fluidity, it tends to render the presence of iron oxide less necessary.

SEC. 87.—*Automatic regulation of fluidity in basic open-hearth slag.*—This matter of fluidity is of vital practical importance, for the slag must run freely from the furnace, else the hearth will soon be filled; furthermore, the slag must be so basic that the hearth is not scorified. The two conditions, fluidity and basicity, determine the nature and amount of the basic additions, for the sum of CaO and MgO can not much exceed 55 per cent. without producing a viscous cinder, neither can the percentage of SiO_2 fall below 10 per cent. unless unusual amounts are present of the oxides of iron, manganese, or phosphorus.

I have advanced this theory of the automatic regulation of fluidity with some hesitation, but it seems to account for a curious relation between the content of SiO_2 and FeO in a large number of basic slags, which are grouped and averaged in Table 40.

TABLE 40.

Relation between SiO_2 and FeO in Basic Open-Hearth Slags.*

Group.	No. of heats in group.	Phosphorus in charge, per cent.	Phosphorus in ingot, per cent.	Limits of SiO_2 in slag, per cent.	Composition of slag; per cent.		
					SiO_2.	FeO.	SiO_2.+FeO.
1	8	1.35	.068	below 10	9.20	18.45	27.65
2	10	1.35	.088	above 10	12.54	14.93	27.47
3	15	0.19	.016	8 to 12 incl.	10.71	25.31	36.02
4	15	0.19	.017	13 to 14 incl.	13.84	21.81	35.65
5	19	0.19	.020	15 to 16 incl.	15.90	18.21	34.11
6	13	0.19	.022	17	17.32	17.97	35.29
7	15	0.19	.025	18 to 19 incl.	18.94	15.50	34.44
8	12	0.19	.023	20 to 22 incl.	21.57	13.58	35.15
9	7	0.19	.059	23 to 27 incl.	25.48	9.04	34.52
10	16	0.10	.014	10 to 13 incl.	12.28	22.18	34.46
11	14	0.10	.012	14	14.47	22.78	37.25
12	15	0.10	.016	15	15.54	21.10	36.64
13	20	0.10	.017	16	16.46	21.32	37.78
14	19	0.10	.015	17	17.47	19.24	36.71
15	12	0.10	.012	18	18.32	20.02	38.34
16	11	0.10	.018	19	19.41	17.66	37.07
17	14	0.10	.020	20	20.53	14.92	35.45
18	21	0.10	.016	21	21.51	14.58	36.09
19	17	0.10	.019	22	22.46	13.41	35.87
20	11	0.10	.022	23	23.41	12.40	35.81
21	9	0.10	.028	24	24.48	11.05	35.53
22	12	0.10	.042	25 to 29 incl.	26.37	10.58	36.95

*The full records of the above charges will be found in Section 45 of my paper on *The Open-Hearth Process*, in *Trans. A. I. M. E.*, Vol. XXII, page 436, *et seq.*

The phosphoric acid was not determined, but it may be taken for granted that an increased proportion of phosphorus in the charge will give higher phosphoric acid in the cinder, and the table shows that in the case of high phosphorus the combined SiO_2 and FeO runs about 27.5 per cent., with medium phosphorus about 35 per cent., and with low phosphorus about 36 to 37 per cent. It is quite true that a difference in manipulation would change the absolute percentages, but the attainment of a certain definite content of $FeO + SiO_2$ seems assured. This conclusion is verified by an examination of the individuals of the original records, for it is found that low SiO_2 is accompanied by high FeO and *vice versa.* This is shown by Table 41 which is composed of the extreme cases of high and low percentages of SiO_2 and FeO, found in the individual heats which compose the groups in Table 40.

TABLE 41.

Maxima and Minima in the Individual Heats Composing the Groups in Table 40.

Initial phosphorus in charge; per cent.	Slag showing maximum SiO_2; per cent.		Slag showing maximum FeO; per cent.	
	SiO_2.	FeO.	SiO_2.	FeO.
1.35	16.50	6.99	9.46	27.72
0.19	27.35	6.63	9.53	34.47
0.10	29.15	8.27	15.66	34.36

It would be entirely wrong to suppose that an increase in SiO_2 has reduced the FeO by simple dilution, for a reduction in FeO from 20 per cent. to 10 per cent. would imply a permanent addition of SiO_2 equal to the entire volume of the slag, and this is manifestly absurd. The conclusion seems inevitable that SiO_2 and FeO replace one another in some way, and that one fulfils some function of the other. As FeO is basic and SiO_2 is acid, this function can not possibly be related to the basicity of the slag or any strictly chemical status, and the only explanation which suggests itself is that both confer fluidity and that there is an automatic regulation of this quality in accordance with the theory before elaborated.

SEC. 88.—*Determining chemical conditions in basic open-hearth slags.*—Just as oxide of iron exists in slag in accordance with favorable conditions rather than with the initial character of the charge, so the content of phosphoric acid is governed by the chemical environment. As a general law it may be said that the capacity of a cinder for phosphoric acid increases with the proportion of bases it contains, and that lime is the most potent of these bases. The most important modification of this law is the necessity for a certain fluidity, since a slag which is very viscous does not seem to be as effective as one which is rendered fluid by oxide of manganese or iron. Thus, although lime is immeasurably superior to oxide of iron as a dephosphorizing agent, nevertheless, as I have shown elsewhere,* a slag containing a slightly higher percentage of FeO is more efficient.

One of the more important determinants of the capacity of slag for phosphorus is the phosphorus itself. The absorption of phosphoric acid is not a case of simple solution (if such a phenomenon exists) like that of salt in water, but it is a union of acid and base, and, therefore, each molecule of phosphoric acid which enters the slag decreases its capacity for more in exactly the same way that silica would. It is impossible to prove this conclusively by ordinary averages, for the additions of lime are usually regulated by the demands of the silica rather than of the phosphorus, and it is a coincidence if the maximum content of phosphoric acid is present.

Moreover, the precise determining conditions vary with each particular combination of the remaining elements, with the intensity of the reducing conditions, and with the duration of the exposure. Thus Table 42 gives examples of slags which were produced under abnormal conditions; the samples were taken from an open-hearth furnace soon after melting, and before an extreme temperature had been reached to give the carbon of the bath its full reducing power to break up unstable compounds.

These slags are especially selected as being extreme instances of high phosphorus for a given silica, and they are therefore valueless as an indication of what may be expected

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* *The Open-Hearth Process. Trans. A. I. M. E.*, Vol. XXII, p. 446.

in regular practice. They do show, however, that there is no such thing as a critical percentage of silica, since a cinder with 37 per cent. SiO_2 may hold 2 per cent. P_2O_5.

TABLE 42.

Unstable Basic Open-Hearth Slags.

Slag.	Composition, per cent.			
	SiO_2.	P_2O_5.	FeO.	SiO_2.+P_2O_5.
1	37.53	2.01	10.26	39.54
2	34.05	3.08	18.45	37.13
3	32.45	3.33	9.36	35.78
4	30.26	5.99	10.08	36.25
5	25.21	8.34	11.88	33.55
6	20.60	10.97	10.90	31.57
7	17.31	16.60	12.15	33.91
8	15.07	23.06	10.53	38.13

The slags in Table 43, although selected somewhat arbitrarily, are fairer examples of the results of regular work. In both Table 42 and 43 there is a column headed "$SiO_2 + P_2O_5$," and the constancy of this total under similar conditions, even with slags of widely varying character, indicates that the total acid content of the slag is the measure of its power to absorb phosphorus.

TABLE 43.

Normal Basic Open-Hearth Slags.

Slag.	Composition, per cent.			
	SiO_2.	P_2O_5.	FeO.	SiO_2.+P_2O_5.
1	20.72	6.36	16.20	27.08
2	19.04	8.24	20.16	27.28
3	12.40	13.73	12.60	26.13

SEC. 89.—*Elimination of sulphur.*—A certain proportion of phosphorus is likely to be volatilized by the heat and carried away in the waste gases. This renders futile any attempts to make accurate quantitative calculations on the chemical history, but otherwise the action is of little importance since it can not be relied on for purification of the metal. This volatilization occurs in greater measure in the case of sulphur, but here also it is entirely impracticable to eliminate any appreciable proportion by this method alone, since volatilization occurs only from the slag, and the action, therefore, presupposes the transfer of sulphur from the metal to the cinder,

and this in turn presupposes a condition which will purify the metal without the *ex post facto* intervention of volatilization.

The removal of sulphur can be accomplished in at least four ways, which will be considered *seriatim.*

(1) By the addition of metallic manganese and liquation of sulphide of manganese. The extent of this reaction is very uncertain, but usually the addition of 0.60 to 0.75 per cent. of manganese in the form of recarburizer reduces the sulphur content about 0.01 per cent.

(2) By the use of manganese ore, which, being reduced by the metalloids of the bath, furnishes metallic manganese. The ore should be added with the original charge in order that it may be thoroughly mixed with the metal. It is very difficult to isolate the effect of this agent from the contemporaneous action of the basic slag with which it must be associated, but there is no doubt that it aids in the purification.

(3) By the action of a very limey cinder. In a former paper* I gave the results of experiments in removing sulphur by ordinary lime slags. The cinder, during melting, was kept high in silica to economize lime, and part of this slag was removed after fusion, and fresh lime added. Notwithstanding the high acid content, the slag after melting held quite an appreciable proportion of sulphur. The final slag, being richer in lime, removed a greater quantity and the results seem to show that, as the silica decreases, the capacity for sulphur increases, but the relation is not as regular as might be wished, and it must be acknowledged that many points are still obscure. The records are given in Tables 44 and 45.

(4) By oxychloride of lime. A process has been devised by E. H. Saniter† whereby sulphur is eliminated from basic open-hearth metal by the use of oxychloride of lime. It is important to note, however, that "in order to attain this result it is necessary, at an early period after the charge is melted, to obtain an exceedingly basic slag, and to add a suitable quan-

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* *The Open-Hearth Process. Trans. A. I. M. E.*, Vol. XXII, p. 446.

† *On a New Process for the Purification of Iron and Steel from Sulphur. Journal I. and S. I.*, Vol. II, 1892, p. 216; also, *A Supplementary Paper on a New Process for Desulphurizing Iron and Steel. Journal I. and S. I.*, Vol. 1, 1893, p. 73.

tity of calcium chloride to it;" and it is further specified that "by a very basic slag is not meant what has hitherto been considered as such, but a step in advance of that with about 50 to 60 per cent. of lime." This point is also insisted upon

TABLE 44.

Basic Open-Hearth Slags after Melting, Arranged according to their Sulphur Content.

Charge Number.	Initial sulphur, per cent.	Sulphur in metal after melting, per cent.	Composition of slag after melting, per cent.				
			S.	SiO_2.	FeO.	CaO.	MnO.
1546	.43	.28	.28	37.53	10.26	34.53	4.66
1611	.20	.14	.26	32.63	10.17	36.25	und.
1608	.28	.17	.22	31.30	10.98	41.45	und.
1628	.20	.16	.21	33.20	9.45	und.	und.
1648	.20	.14	.21	34.37	6.57	und.	und.
1567	.28	.18	.20	30.26	10.08	45.26	5.42
1646	.20	.15	.18	33.97	11.61	und.	und.
1626	.20	.11	.18	36.43	5.04	und.	und.
1564	.28	.10	.17	32.45	9.36	45.05	5.49
1555	.28	.22	.14	30.63	13.41	39.17	7.15
1630	.20	.09	.14	25.57	8.01	und.	und.
1606	.28	.19	.12	35.79	18.00	33.13	und.
1569	.28	.19	.08	34.05	18.45	35.09	6.25

TABLE 45.

Basic Open-Hearth Slags before adding Recarburizer, Arranged according to their Sulphur Content.

Charge number.	Initial sulphur, per cent.	Sulphur, after melting.		Sulphur in ingot, per cent.	Composition of slag before adding the recarburizer, per cent.				
		Slag, per ct.	Metal, per ct.		S.	SiO_2.	FeO.	CaO.	MnO.
1608	.28	.22	.17	.095	.61	12.73	26.91	43.99	und.
1611	.20	.26	.14	.054	.58	10.45	26.19	45.85	und.
1555	.28	.14	.22	.086	.56	13.78	26.91	42.14	4.85
1606	.28	.12	.19	.100	.54	12.90	31.14	38.58	und.
1569	.28	.08	.19	.089	.48	15.90	18.63	und.	und.
1630	.20	.14	.09	.062	.43	16.26	19.98	49.50	und.
1546	.43	.28	.28	.120	.36	18.67	24.84	37.23	4.44
1567	.28	.20	.18	.062	.33	14.85	23.49	45.74	4.54
1564	.28	.17	.10	.089	.33	19.18	16.11	49.98	4.58
1648	.20	.21	.14	.090	.26	17.97	23.94	44.41	und.

by Stead,* who reviews the experiments and states that the chloride is used "in conjunction with an excess of lime over and above what is usually employed." He gives analyses of slag and metal for two charges, and a summary of these is

* *On the Elimination of Sulphur from Iron. Journal I. and S. I.*, Vol. II, 1892, p. 260.

given in Table 46. The results of a more complete investigation of one charge are shown in Table 47, the data being taken from a paper by Snelus.*

The sulphur after melting is higher than the calculated initial content, but this is probably due to incorrect sampling and to the absorption of sulphur from ore and gas, since the percentage of sulphur in the slag shows that a considerable amount was taken from the metal. After melting, the carbon was reduced to .20 per cent., and one hour later it was .09 per cent., but it was necessary to hold the charge in the furnace

TABLE 46.

Elimination of Sulphur by Calcium Chloride.

Heat.	Composition, per cent.							
	Metal.		Slag.					
	Sulphur.		After adding $CaCl_2$.			At time of tapping.		
	Initial.	In steel.	SiO_2.	CaO.	S.	SiO_2.	CaO.	S.
1	.37	.047	10.75	54.65	1.25	10.20	48.98	.65
2	.17	.055	14.45	44.34	.53	11.75	47.86	.57

TABLE 47.

Detailed Data on the Elimination of Sulphur by Calcium Chloride.

Open-hearth charge: 80 per cent. white iron, 20 per cent. scrap, the whole averaging about .30 sulphur.

Time of taking sample.	Composition of metal, per cent.		Composition of slag per cent.		
	C.	S.	SiO_2.	CaO.	S.
After complete fusion	.20	.320	18.30	49.24	.315
1 hour after melting	.09	.181	15.00	49.60	.576
4 hours after melting	.06	.093	11.60	55.64	.659
Steel, 5½ hours after melting .	.10	.040	10.80	57.00	.645

for four and one-half hours after complete decarburization, and to dose it with calcium chloride in the proportion of 50 pounds to the ton of metal, in order to remove the sulphur, a delay which is decidedly objectionable. The oxychloride, however, conferred fluidity upon the cinder, and made it possible to carry as high as 57 per cent. of CaO, and it is probable

*Report upon the Saniter Desulphurization Process. Journal I. and S. I., Vol. I 1893, p. 82.

that this increased mobility and corresponding activity rendered the lime more efficacious in absorbing sulphur. This point is not satisfactorily settled, for notwithstanding the learned discussions and investigations following Saniter's experiments, the inner history of desulphurization is still unwritten.

A quantitative investigation that I made into the elimination of sulphur by weighing and analyzing the slags from three of the charges given in Table 44, showed that about 36 per cent. of the sulphur was unaccounted for, having probably been carried away as sulphurous acid (SO_2) in the waste gases. The fact that both sulphur and phosphorus thus escape in an intangible form and in uncertain quantities, renders quantitative work on basic slags very unsatisfactory. Moreover, a sample of slag is not always representative, for on some heats portions of the basic additions remain sticking to the hearth, while on others old accumulations of such deposits dissolve in a charge to which they do not belong.

SEC. 90.—*Removal of the slag after melting.*—When the stock is properly charged, the greater part of the basic addition becomes an active agent during the melting of the charge. Especially when ore is used the intense action oxidizes a considerable proportion of the phosphorus during the melting, and the slag after fusion contains oftentimes a high percentage of phosphoric acid. The idea has occurred to numberless metallurgists that this first slag should be removed in order to get rid of its phosphorus and silica and thus give the opportunity for a new and purer slag having a greater dephosphorizing power, but the practical difficulties in the way have always compelled a relinquishment of the plan. The exact height of the metal in the hearth is always varying with the filling of the bottom and with the frothing of the charge, so that there is danger of losing metal if a taphole is opened much below the level of the upper surface of the slag. On the contrary, if the slag is tapped from its upper surface there is no force to the stream and it is constantly chilling as it runs.

The complete removal of the slag can be accomplished, however, by the use of a tilting furnace, for the entire charge can be poured out and only the metal returned to the furnace. The possibility of thus disposing with certainty of nearly all

the silica of the charge, and of whatever phosphorus and sulphur may be in the slag after fusion, opens up a field of speculation as to the best practice in different cases. Given a pig-iron containing a considerable proportion of silicon and with low phosphorus, it will be an advantage to have the first slag as high in silica as possible so as to avoid the addition of a corresponding quantity of lime. When the metal is returned to the furnace, the small amount of cinder which sticks to the hearth, together with the silica of the ore and a little extra lime, will furnish slag enough to remove the phosphorus. This practice, however, cannot be carried to an extreme, for if the amount of lime is reduced to such an extent that the slag after melting contains much over 30 per cent. of silica, the hearth will be badly scorified. If melted pig-iron is used, this difficulty disappears, for ore may be added to a bath of pig at the rate of 2000 pounds per hour and the silicon be rapidly oxidized. The slag so produced in the absence of a full supply of lime may run about 30 or 35 per cent. of silica and 25 to 35 per cent. of iron oxide. This would scorify the hearth if left long enough in the furnace, but it should be removed after the silicon is oxidized, for during the oxidation of carbon from a content of three per cent. down to about one per cent. the frothing is very violent, and if the slag is not removed there will be considerable trouble and delay.

If the pig carries much phosphorus or sulphur, the first slag should not be too rich in silica, for under these conditions the full content of the impurities will remain in the metal and it will be necessary to make a large volume of cinder to remove them. The better way in this case is to form a slag rich enough in lime to carry a good proportion of phosphoric acid and sulphur, and liquid enough to pour well. When the metal is returned to the furnace a second slag can be made from fresh lime, and it will be evident that it will more readily absorb the impurities than a cinder which is already partly satisfied.

SEC. 91.—*Automatic formation of a slag of a given chemical composition.*—In such practice there might appear to be a difficulty in properly regulating the composition of the second slag, but the records in Tables 44 and 45 show that such is not the case, for, in the heats there given, a part of the

slag was removed soon after melting. Quite a difference will be found between the first and second slags, but this is because the first slag was purposely made high in silica in order to save lime. When it is required to maintain a similar composition throughout the heat, it can be done in basic as well as in acid practice, as shown by the average slag analyses of twenty-seven heats given in Table 48.

TABLE 48.

Average Slag Analyses of Twenty-Seven Basic Open-Hearth Heats.

Slag.	Composition, per cent.			
	SiO_2.	P_2O_5.	CaO.	FeO.
After melting	14.35	15.53	45.07	9.00
Before tapping	12.40	13.73	45.40	12.60

Four-fifths of the lime was added with the charge, and the remainder, together with 400 pounds of ore, was used after melting, but in spite of the incorporation of this basic material into the slag during the interval between the two stages at which the samples were taken, it will be seen that by careful supervision and through the action of the internal chemical forces, a remarkably uniform composition was maintained, which proves conclusively that the manipulations of the basic process are as completely under control as the operations upon the acid hearth.

SEC. 92.—*Recarburization and rephosphorization.*—Recarburization is carried on in the same way as in acid work, and is subject to the same general laws. A complicating condition is often added when either the stock or the ore contains any considerable proportion of manganese, for the decarburized metal may then hold as much as .20 or .30 per cent. of Mn. Not only must this be allowed for in making the final addition, but it will also be found that the bath contains less oxygen under these circumstances, and therefore there will be less loss of metallic manganese during the reaction.

In basic practice there is a factor not present in acid work, in the danger of rephosphorization, or the return of phosphorus from slag to metal. In the basic Bessemer this is a source of considerable trouble, but in the open-hearth the recarbu-

rizer is almost always added in a solid state and the metal probably contains less oxygen, so that the reaction is less violent. Moreover, during the solution of the ferro, the slag is constantly at work with its dephosphorizing influence, so that the sum total of the reactions may even show a decrease in phosphorus. Other things being equal, it would seem probable that a slag containing a high percentage of phosphoric acid will hold this component less firmly than a purer cinder, and I have tried to illustrate this point* by experiments the results of which may be summarized as follows:

(1) With slags containing under 5 per cent. P_2O_5 and not over 20 per cent. SiO_2, the rephosphorization need not exceed .01 nor average over zero per cent.

(2) With slags containing from 5 to 10 per cent. P_2O_5 and not over 19 per cent. SiO_2, the rephosphorization need not exceed .015 nor average over .005 per cent.

(3) With slags containing from 10 to 15 per cent. P_2O_5 and not over 17 per cent. SiO_2, the rephosphorization need not exceed .02 nor average over .005 per cent.

(4) With slags containing from 15 to 20 per cent. P_2O_5 and not over 12 per cent. SiO_2, the rephosphorization need not exceed .02 nor average over .01 per cent.

In using phosphoritic stock it is not safe to presuppose the elimination of phosphorus below .04 per cent. until the carbon has been lowered to about .08 per cent. Hence, to make rail steel it is necessary to eliminate the carbon to that point and then add the required amount of recarburizer, as in the Bessemer process. It is impracticable to use melted spiegel-iron in open-hearth practice, because the charges come so irregularly and at such long intervals that a cupola becomes chilled, but it has been found possible to add finely divided carbon in the ladle, its absorption by the metal being so rapid that the results are quite regular.

Several ways of doing this have been devised, the most successful of which has been very fully described by Dr. Wedding†. Powdered "anthracite" coal is mixed with about 7 per cent. of burned lime and with sufficient water to make a

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* *The Open-Hearth Process. Trans. A. I. M. E.*, Vol. XXII, p. 484.

† *Stahl und Eisen.* 1894, pp. 473 and 533; also 1895, p. 570.

plastic mass, and is then formed into bricks. These are dried thoroughly to expel all the uncombined water, and are then ready to be fed into the ladle as the heat is poured.

The escape of the combined water in the lime causes the bricks to crumble to pieces when in contact with the melted steel, but this crumbling is gradual, so that the carbon is fed to the metal continuously and the bath is able to absorb it as fast as it is set free. This moisture also creates a constant motion of the bricks and acts as a mechanical stirrer.

I am informed by Mr. George W. Gœtz, of Milwaukee, that the kind of coal which is referred to by Dr. Wedding is a rather hard bituminous coal and not at all what is known as "anthracite" in America, and that the practice at different works leads to the conclusion that coke dust or other similar forms of carbon would answer equally well.

CHAPTER XII.

CONSIDERATIONS ON CERTAIN COSTS OF MANUFACTURE.

SECTION 93.—*Conditions determining the supply of scrap.*—It has been shown that the Bessemer process requires for its operation only the product of the blast-furnace, but that it can use to advantage, for the cooling of the charge, a small part of the scrap which is produced in working its product into finished shapes. The remainder of the scrap is a by-product which can only be used at an augmented cost by running on a very high-silicon iron.

In the open-hearth furnace, on the other hand, it is advantageous to use about 75 per cent. of scrap in the mixture. This is more than will be produced from the output of the furnace in any series of finishing processes, and hence in a plant making all its steel by converters there will always be a surplus of scrap which is worth less to the producer than pig-iron, while in a plant making all its steel in open-hearth furnaces there will be a deficit of scrap, and the plant will be willing to pay more for it than for pig-iron on account of the advantages in time, fuel, and product to be saved by its use. The scrap also has an additional value from the diminished waste as compared with pig-iron, due to the smaller content of foreign elements.

The simple relation whereby the Bessemer has a surplus of what the open-hearth needs, is complicated by the fact that miscellaneous material is continually being thrown on the market from worn-out rails, boilers, and general structures. In the past such scrap was mostly wrought-iron, but with the increasing use of steel in construction the percentage of steel in such scrap is rapidly increasing. For the acid open-hearth, common wrought-iron is unsuitable on account of the high

phosphorus it contains, and although it may be used in the basic furnace, it is usually worth more to rework into finished iron than to remelt.

This supply of miscellaneous scrap is evidently entirely unconnected with the business of making steel, and hence it may and usually does happen that at places most remote from the great producing centers, steel scrap is a drug upon the market. Such a place may be a very good situation for an open-hearth furnace provided the product can be economically put into a shape to be sold in the local market, but it must be borne in mind that as soon as there is a demand for the scrap it ceases to be a drug and becomes a commodity.

Sec. 94.—*Comparison of the cost of the Bessemer and open-hearth processes.*—Even with cheap scrap it is usually out of the question for a small open-hearth plant to compete with the Bessemer in the manufacture of common material, although the difference in the strictly metallurgical items is not as great as usually supposed. A comparison of the details of the two processes will show that the furnace requires more fuel than the cupola, but this is counterbalanced by the fact that the open-hearth does not need a battery of boilers to supply a blowing engine. The repairs to hearth and roof will be matched by the relining of cupolas and vessels and the very expensive vessel-bottoms, while the difference in labor is not prohibitory.

The greater cost of making steel by the open-hearth arises almost altogether from the greater output in the Bessemer of a regular grade of metal, cast in regular sizes of ingots. Up to within a short time there has been no true open-hearth plant in this country. There have been several furnaces connected with one establishment, but the first systematic arrangement is the work of the last few years.

In a small establishment the cost of working the product into finished steel is greatly enhanced. With small shapes and bars it often happens that a small finishing mill can run economically on a production of only twenty-five or thirty tons a day, but the manufacture of the billets is a different matter. The ingots should be at least fourteen inches square to provide for sufficient work upon the metal, and the reduction of these to billet form requires a strong and heavy mill.

Such a mill, if at all capable of doing the work, can handle four hundred tons a day just as well as twenty-five, and with the small output the boilers and furnaces must waste fuel, and men must stand waiting, and it is evident that each ton of product must bear a heavy financial load. Moreover, when a charge does not show the chemical composition desired the small plant may have no use for it, and to some extent it is a loss, while in the larger steel works, with diversified products and a wide market, it seldom happens that a heat is not applicable to some order.

SEC. 95.—*Development of large plants.*—These and many other considerations render it very difficult to make steel economically in a small open-hearth plant, and the tendency of modern steel manufacture is toward concentration of the business of producing the raw material. Blooms, slabs, and billets may best be made in a large establishment, fitted for handling a thousand tons a day, with a proper outfit of laboratories and testing apparatus, with a management fitted for meeting all problems in new specifications, and with a market so varied that steel may be used for the purposes for which it is fit, rather than for the special order on which it was made. In the manufacture of plates it has been the practice to build an open-hearth plant in connection with a plate mill and roll the plates direct from the ingot, but this system has been superseded in some works by the erection of mills designed to roll very large ingots and cut them into pieces suitable for plates. The extra expense is counterbalanced in some measure by the reduction in pit-work due to the smaller number of ingots handled, but it does not seem probable that the cost of heavy slabs can ever be brought down to that of ingots of the same weight, although in sizes under 1000 pounds the difference will not be great. The slab will give less scrap than an ingot in rolling into a plate, and this must be counted in the estimate of cost; but the strongest argument in favor of preliminary slabbing is the greater uniformity and homogeneity of the product.

It is possible that some open-hearth plants may be able to make common steel in competition with a Bessemer plant where the iron is melted in cupolas, but it is doubtful whether they can compete with a large converting plant using

iron direct from the blast-furnace, even though this point be contested by the use of direct metal in the open-hearth. The Bessemer system was worked out to its limit in years gone by under the spur of immense profits, an unlimited market, and ample capital, but the open-hearth has been a side-show in the big steel works, and a sort of shop in the smaller establishments. With the increasing demand for steel in construction and the constantly increasing stringency of specifications in order to procure the best material, the field of the open-hearth is widening every day, and the result will be an improvement in the quality and a lowering of the price.

Sec. 96.—*Determining economic conditions of steel manufacture.*—The foregoing comparison of the Bessemer and open-hearth has failed to give any definite data on the items of cost, because in different districts there are enormous variations in the cost of raw material, of fuel, of refractories, and of labor. For the same reason it is impossible to give the relative position of the acid and basic processes. The decision in the question between acid and basic linings for the converter oftentimes settles itself, for an acid Bessemer can not well be run in Alabama with its phosphoritic ores, and a basic Bessemer would be out of the question in the Lake Superior district. In such cases the only problem is whether either process will pay at all, and this can not always be decided by the simple natural advantages, however marked they may be. There are places in the uninhabited valleys of the northern Rocky Mountains where coal fields and ore beds lie waiting for the coming of the metallurgist; but in such a district the installation to-day of a plant with its dependent community would be done at an enormous financial sacrifice, the labor which could be obtained at exorbitant rates would be unreliable and inefficient, and the cost of transporting the product to market would be prohibitory. The financial equation of a great industry is a combination of social and metallurgical factors. A district where the pig-iron contains over 2.00 per cent. of phosphorus is the natural field for a basic Bessemer; where it contains under 0.10 per cent. is the field for an acid Bessemer or open-hearth; and where it contains any proportion between these extremes is the field for a basic open-hearth; but these con-

ditions must be supplemented not only by cheap fuel, but by fixed labor conditions and cheap transportation to a sufficient market. These platitudes seem so axiomatic that they could be called superfluous if their disregard had not caused the waste of many millions in ill-starred enterprises.

SEC. 97.—*Comparison of the costs of the acid and the basic-Bessemer processes.*—In a district where both high and low-phosphorus irons are obtainable, and where the impure metal costs one or two dollars less per ton, the question arises as to whether an acid or a basic-lined converter will produce the cheaper steel. The cost of labor in manufacture and repairs must always be more in basic than in acid work, the exact amount depending on the scale of wages. In Germany, where a workman receives seventy-five cents per day, the conditions differ from those in our own country where nearly twice that sum must be paid for twelve hours of common labor. Moreover, this proportion of double the foreign pay holds good through all the grades of work, so that while the American day laborer receives only seventy-five cents more per day, the American skilled workman receives two dollars more.

This factor of labor is not confined to the converting-room but forms a large part of the cost of every article used; it appears in the manufacture of the iron, the coke, and the lime, in the preparation of the refractories, in the transportation and handling of the miscellaneous supplies, in the repairs and shop work, and in the salaries of clerks and engineers.

These conditions place the basic-Bessemer process in America on an entirely different footing from that which it occupies in other countries, and it is doubtful whether there is any place in the Northern States where the basic converter can successfully compete with the acid plants that are supplied from the mines of Lake Superior and Cuba. Even though these financial difficulties should be entirely overcome, there would still remain the feeling of uncertainty regarding the quality of the product, which would be a strong argument against its general use in structural engineering.

SEC. 98.—*Comparison of the costs of the acid and the basic open-hearth processes.*—The relation of the acid and basic linings of the open-hearth furnace to each other is entirely different from the relation existing between the modifications

of the Bessemer process, for the basic open-hearth is not confined to high-phosphorus stock. When it does use such material it stands more nearly on a level with the basic converter in the danger of rephosphorization from a very phosphoritic slag, but in the case of the Bessemer there is no middle ground, for high-phosphorus iron must be used to produce heat, while in the open-hearth a medium mixture may be used containing less than 0.75 per cent. of phosphorus. With such a bath, and with proper care, the quality of the steel may be prophesied with certainty; and when a particularly pure article is wanted, a better stock may be charged to insure a low content of phosphorus in the steel.

To these primary advantages is added the feasibility of taking tests before tapping. In the Bessemer such tests are very crude, since the bath cools too rapidly to allow of long delay, but in the open-hearth there is opportunity for rapid chemical determinations in the laboratory. Moreover, much less danger of rephosphorization exists, for there is perfect control over the nature of the slag and less mixing of metal and cinder during recarburization.

Thus the process on the basic hearth differs radically from that in the converter, and it follows that the acid and basic modifications of open-hearth work are more nearly alike than the acid and basic Bessemers, and that there is no such ground for questioning the reliability of basic open-hearth steel as there is of basic Bessemer.

It is also necessary to consider that it is practicable, and not at all an uncommon practice, to use the same stock in basic as in acid furnaces. When this is done and nothing is charged containing over .10 per cent. of phosphorus, it would seem as if the last bulwark of the prejudiced mind had been overthrown.

In thus comparing the acid and basic linings of the hearth, it is well to bear in mind that the finest kinds of acid open-hearth steel are made by using charcoal blooms, puddled iron, and washed metal, all of which are made by a basic process and oftentimes from a very common sort of pig-iron. There seems, therefore, to be no good ground for prohibiting the use of basic open-hearth steel, since the timid engineer may insist, if he will, that all stock shall contain less than .10 per cent. of phosphorus.

SEC. 99.—*Method of manufacture as affecting the quality of the steel.*—It is urged by some that the engineer has nothing to do with the manufacture of the steel but that his province begins with the rolled bar. All this will be true when the engineering profession discovers a system of tests which will find out everything about steel, but this has not yet been done. The woful mistakes made by Fairbairn, Euverte, R. W. Hunt, and others, in testing phosphoritic steels, show that the engineering laboratory must be supplemented by chemical analyses. It is well not to assume the truth of all tradition, but if there is any one fact which seems demonstrated it is that phosphorus will hide its true character in the testing machine, but will certainly make itself known at some future time. It is a pity that this can not be received as proven, so that each newly-fledged engineer will not insist upon learning it at the expense of money and of life.

There is a corollary to be drawn from these facts regarding phosphorus, which may be stated as follows: Since the true quality of steel does not show itself in the testing machine, it is idle to claim that Bessemer is as good as open-hearth metal simply because it gives as good results under ordinary tests. The prejudice against Bessemer steel is the outgrowth of long experience and many failures, and it may not be disregarded. The prejudice against basic open-hearth metal rests on an entirely different foundation, having as its starting point the supposition that bad raw material must give a bad product. In acid work this is most certainly true, but on the basic hearth the objectionable element is carried away in the slag, and the doctrine is left entirely unsupported. The true test is the behavior in actual use, and no one will claim that American open-hearth basic steel has failed in this respect, for it has not yet had extensive trial and where used has made an excellent record.

SEC. 100.—*Popular errors regarding the basic open-hearth process.*—There is one general misunderstanding in the engineering profession concerning the basic process which needs to be corrected. It is currently believed that the basic open-hearth is a kind of magic retort into which almost anything in the shape of iron can be treated at a minimum cost and converted into a metal just good enough to deceive the en-

gineer; and it is also a prevailing opinion that the manufacturer would always like to have the privilege of making steel in such a furnace on account of the cheapness of the raw material. It may not be amiss, therefore, to say that in the Northern and Eastern States the cost of making ordinary structural steel is greater on the basic than on the acid hearth. This arises from the fact that mill-iron costs very nearly as much as Bessemer-iron, and that pig-iron usually constitutes only one-third or one-half the charge. The rest is scrap, and there is no cheap phosphoritic low-carbon material in the market, for wrought-iron is worth more to re-work than to melt and sells at a higher price than steel scrap. If the charge is one-third pig-iron and two-thirds scrap, the advantage in stock will be only one-third of the difference in price between good and bad iron, and this difference is very seldom as much as two dollars per ton, so that the gain may easily be covered by the basic additions and the additional labor and repairs. If a greater proportion of pig be used, the waste, the extra time necessary, the increased fuel, and the lessened output will generally counterbalance the gain.

SEC. 101.—*Relative cost of stock in the Pittsburg district for making steel by different processes.*—Leaving out of consideration the incidental running expenses, it may be well to consider one or two extreme instances to see what bearing the nature of the raw material has upon the cost of the product. The impossibility of giving a general value to pig-iron and scrap is recognized, but if the open-hearth and the Bessemer are charged the same price for the same stock, and if it is assumed that scrap is worth one dollar more than pig-iron, the error will not be great in the comparison. It is true that Bessemer pig-iron has been made for less than eleven dollars per ton in Pittsburg, but this was only rendered possible by a complete disregard of those royalties and profits on the ore, the coke, the transportation, and the manufacture, which rightfully belong to the capital invested and which must assuredly be paid in the long run to insure the continuance of industrial life.

The waste is assumed to be the same as in acid practice, for although there is twice as great a volume of slag, it contains only half as great a percentage of iron, but the slight

gain in cost of stock is fully overcome by the extra cost of hearth material.

The substitution of any other values in the calculation is a matter of simple arithmetic, but it will be evident that no radical change can be made in the comparison of acid and basic practice when using similar mixtures. The field for the basic hearth in the north is in making the finer qualities of steel with a low content of phosphorus. It is difficult to give the cost of low-phosphorus acid steel owing to the wide variations in the cost of pure stock, but it may be roughly stated that pig-iron and scrap containing less than .04 per cent. of phosphorus are worth $4.00 per ton more than common metal averaging about .10 per cent.

PITTSBURG DISTRICT.

ACID BESSEMER.

Ten tons pig-iron @ $11.00	$110.00
Product, 9 tons steel.	
Cost of stock, $12.22 for each ton of finished product.	

ACID OPEN-HEARTH.

Six tons pig-iron @ $11.00	$ 66.00
Eighteen tons scrap @ $12.00	216.00
One-third ton best ore @ $3.75	1.25
Total	$283.25
Product, 23 tons steel.	
Cost of stock, $12.32 for each ton of finished product.	

BASIC OPEN-HEARTH.

Six tons pig-iron @ $10.00	$ 60.00
Eighteen tons scrap @ $12.00	216.00
One-third ton best ore @ $3.75	1.25
Three thousand pounds pure burned lime	6.00
Total	$283.25
Product, 23 tons steel.	
Cost of stock, $12.32 for each ton of finished product.	

SEC. 102.—*Economic conditions in the South.*—The conditions in Alabama and Tennessee are widely different from those which have just been discussed. Considering first the case of a works which purchases no outside low-carbon material, it will be evident that the amount of scrap available will be the amount which is produced at the works, and this will be about 30 per cent. of the ingot weight, or about 25 per cent. of the charge. The proportion of pig-iron will accordingly be about 75 per cent.

The high sulphur and poor quality of southern fuel, and the high silica in the coke and ore, will render very difficult, if not impracticable, the economical manufacture of pig-iron

which shall be low in both silicon and sulphur. It will be much safer to make regularly a product slightly high in silicon, which is only objectionable, rather than to often make high sulphur, which is fatal. In the following assumed composition the sulphur is put at a workable amount, while the silicon is placed at what seems a fair percentage.

ALABAMA IRON.

Eighteen tons pig-iron: Si, 1.50 per cent.; P, 0.75; S, 0.10; Mn, 0.25; C, 3.50.

Six tons scrap: C, 0.10; Mn, 0.50; P, .05; S, .05.

Average charge, 53760 pounds.	Si, 1.12 per cent. = 602 pounds producing 1290 pounds SiO_2.
	Mn, 0.30 per cent.
	P, 0.58 per cent. = 312 pounds producing 715 pounds P_2O_5.
	S, 0.09 per cent.
	C, 2.65 per cent.
Total oxidizable metalloids, 4.74.	

About 8000 pounds of ore will be necessary, and if this carries 3 per cent. of silica, there will be an additional 240 pounds, making 1530 pounds of silica. If the final slag contains 19 per cent. of SiO_2, 9 per cent. of P_2O_5, and from 45 to 50 per cent. of CaO, it is evident that there must be added two and one-half times as much CaO as there is SiO_2, or about 3825 pounds CaO, which is equal to 4780 pounds of ordinary burned lime. This lime will run about 4 per cent. in silica, thus furnishing 191 pounds. Allowing for this, there is a total of 1721 pounds of silica requiring 4300 pounds of lime. The final slag will weigh 8000 pounds and will contain about 15 per cent. of combined iron and 5 per cent. of shot, making about 1600 pounds of iron which will be carried away, or about 3 per cent. of the charge. Together with the 4.74 per cent. of oxidizable metalloids there will be theoretically a loss of nearly 8 per cent., or 4300 pounds. The ore will supply more than this amount of metallic iron and hence, by calculation, the weight of metal tapped should equal the weight charged. Experience proves that this is not quite true, for there is always a certain quantity of dirt entering with the stock, as well as a scorification of hearth, walls, and roof, and since all such foreign material increases the volume of slag, and since there will also be a certain loss of metal down the ports, it follows that there will be a deficit, which in the following calculation is assumed to be about two per cent. The summary is as shown on the following page.

It may be said that some iron has been made in Alabama for less than $7.00 per ton, but it is very doubtful if the average cost for any furnace, for a period of five years, would be any lower if bad iron were marked off at its real value, and if all the general and operating expenses, together with the depreciation and interest charges, were properly distributed. It is more probable that a higher figure would more fairly represent a healthy industrial and financial situation.

BIRMINGHAM DISTRICT.

Eighteen tons pig-iron @ $7.00	$126.00
Six tons scrap @ $7.00	42.00
Three and one-half tons pure ore @ $4.50	15.75
Four thousand three hundred pounds pure burned lime @ 16 cents per bushel	8.60
Total	$192.35

Product, 23.5 tons of steel.
Cost of stock, $8.19 for each ton of finished product.

It will be seen that this cheap stock has given an advantage of $4.00 per ton over the Pittsburg district, but this will be overcome to a great extent by the delay in melting the larger quantity of ore and lime, and by the lengthening of the period of oreing due to the unwieldy volume of slag. Taking into consideration the extra wear of the hearth with consequent repairs, and the reduced capacity of the furnace when large quantities of slag are produced, it is probable that a plant will not make much more than half as much steel in a year under this practice as it would if the charge were made up of good pig-iron mixed with sufficient scrap, and this is equivalent to saying that the cost of fuel and repairs will be doubled; the skilled labor per ton will be much increased on account of the decreased product, while the common labor keeps pace with the extra stock and slag to be handled. The above calculation assumes that the pig-iron is cast in chills so as to be free from sand or is put into the furnace when melted, for if it is cast in sand the waste and the volume of slag will be enormously increased. It also calls for the use of pure lime and for rich ores, the latter probably requiring transportation from Lake Superior, and experience will prove that these specifications are in the line of true economy.

The contents of silicon and sulphur are not what might be wished, but they are fully as low, when considered together, as can regularly be made by the average furnaceman from

the silicious ores and the sulphurous, weak, and silicious cokes of Alabama. The difficulty of making low-silicon, low-sulphur irons in this region has been recognized by all metallurgists, and various projects have been pushed forward whereby irons high in silicon could be handled, it being assumed that if sufficient leeway is given in this element the sulphur can be eliminated by a hot-working blast-furnace. The most attractive method is what is known as the duplex process, by which the silicon is removed in a converter and the metal then transferred to a basic open-hearth for the elimination of phosphorus. That this is a comprehensive and perfectly feasible system cannot be denied, but in the opinion of most steel makers the expense of the operation will be prohibitory. A careful calculation of the waste and scrap in Bessemerizing and reworking, and a consideration of the incidental expenses incident to such a complex plant, render the installation of such an outfit more attractive to the constructive contractor than to the investor.

SEC. 103.—*Desiliconization by means of basic slag.*—Another proposition which made quite a stir in the newspapers at one time, consists in pouring the pig-iron into a ladleful of melted basic open-hearth cinder and burning the silicon by the oxygen contained in the slag. Certain experiments have been chronicled showing that the action does take place and that the silicon is in great measure removed, but in the face of these records I propose to argue that there is some mistake and that the importance of the reaction has been much overestimated. In experimental work it is quite possible to pour a small amount of metal through a large quantity of slag, but in continuous practical operation it is plain that the metal of one charge can be treated only with the slag from a previous charge, and the problem immediately arises of finding the amount of slag on each heat. This is a rather difficult problem, for the volume of slag is entirely dependent upon the weight of silica to be satisfied, and this weight of silica is dependent upon the amount of silicon in the charge, and this in turn is dependent on the success of the desiliconizing operation. If the silicon of the pig is removed in the preliminary treatment, then only a small amount of slag will be produced and the success of the next desiliconization will

be jeopardized in exact proportion. Leaving out of account this history of self-destruction, and neglecting all practical difficulties in keeping the cinder liquid during the pouring with its attendant frothing, it will be assumed that a heat is made up of eighteen tons of melted pig-iron and six tons of scrap, with a production of 8000 pounds of slag containing 18 per cent. of FeO. It would be easy to make a more favorable slag by having a higher content of iron oxide, but this would be a sacrifice of every other desideratum. It will also be assumed, although so perfect a reaction is improbable in regular practice, that by the pouring of the iron through the slag this FeO is reduced to 6 per cent. Under these conditions 12 per cent. of 8000 pounds, or 960 pounds, of FeO will be reduced, furnishing 213 pounds of oxygen, which will unite with 186 pounds of silicon. Calculation shows that this is 0.46 per cent. of the 40320 pounds of pig-iron, so that under assumptions which are certainly roseate, there is a possible elimination of less than half of one per cent. of silicon. That this would be a decided benefit can not be questioned, but it can hardly justify the confident proclamation that the basic question in the South has been forever solved.

In localities where scrap can be obtained the difficulties will be less, since a smaller amount of pig-iron can be used and there will be a corresponding reduction in the weight of silicon and phosphorus. It will be found, however, that the proportion of pig-iron must be very nearly half of the total charge, in order that the bath shall be high enough in carbon, after melting, to allow the removal of the phosphorus and sulphur.

A reduction in the initial content of silicon in the pig-iron will help matters more than anything else, but it is hardly probable, as before remarked, that the average will be any lower, over a long period of time, than the figure which has been assumed in the foregoing calculations. The use of a tilting furnace, and the removal of the slag, have been discussed in Section 90, and it is believed that this system would be very advantageous in handling the irons of the South.

CHAPTER XIII.

SEGREGATION AND HOMOGENEITY.

SECTION 104.—*Cause of segregation.*—Every liquid has a critical point in temperature below which it may not cool without freezing into a solid state. This transformation takes place by the rearrangement of the molecules into crystals, and in this rearrangement there is a very strong tendency for each crystal-forming substance, whether it be an element or a compound, to separate from any other substances with which it may be mixed. This tendency will result in a very perfect isolation when the substances have little affinity for each other and freeze at widely different temperatures. Under these circumstances, if the temperature be very slowly lowered, the more easily frozen substances will almost completely crystallize out, leaving the more fusible in a liquid state.

It will be evident, however, that the completeness of the separation will be lessened by a hastening of the rate of cooling, or a greater similarity between the freezing points of the mixed substances. It will also depend upon the proportion of the ingredients, for it will be more difficult for a crystal to form when its constituent molecules must find their way out of a large mass of a foreign medium, and such a crystal after so forming will be more likely to contain a certain proportion of the associated substances. Under unfavorable circumstances, as when the rate of cooling is rapid, or when the substances have nearly the same freezing temperature, or when they have an affinity for each other, the differentiation may be so much interfered with that there is no appreciable separation of the components.

All these unfavorable conditions are present in the solidification of steel.

First; the temperature of a charge, when it is poured from a converter or from a furnace, is seldom more than 50° C. above the point of incipient congelation.

Second; the absolute temperature is so high, when compared with everything with which it comes in contact, that both conduction and radiation proceed with excessive rapidity.

Third; in the manufacture of ingots for plates, beams, angles, and other rolled or hammered structural material, it is the universal practice to cast the steel in direct contact with a thick iron mold, and the absorption of heat from the outside of the liquid is so rapid that a solid envelope is almost instantly formed, while the conducting power of this envelope is so great that the heat is continually carried from the interior to the surface.

Fourth; the different substances that compose the steel have so many strong affinities for each other, and combine in so many ways, that it is a gratuitous hypothesis to assume the existence of a definite carbide, or sulphide, or phosphide of iron, or a carbide, sulphide, or phosphide of manganese.

No matter how high or how low the content of metalloids in the steel, there is always a tendency toward the separation of crystals which are lower in carbon, sulphur, and phosphorus than the average, so that it is logical to conclude that there is a tendency for pure iron to crystallize, but that this is prevented by the strong affinity it has for carbon, sulphur, phosphorus, silicon, manganese, and copper. This affinity, taken in conjunction with the rapid cooling, almost prevents the differentiation until a very thick envelope has formed on the outside of the ingot to check the loss of heat. Moreover the process of segregation is self-corrective to some extent, since with every step in the contamination of the interior liquid there is an increasing tendency to the formation of impure crystals.

The liquid center is not entirely homogeneous, for, as the impurities are eliminated from the solidifying envelope, they form alloys or compounds which are more fusible and of lower specific gravity than the steel itself, so that they float on the surface of the interior lake. As the level of the metal sinks during solidification, this scum will be deposited as

a film on the walls of the pipe cavity, while the history will end by the solidification of a highly impure mass in the apex of the inverted cone.

When there is only a small proportion of sulphur, or phosphorus, or carbon, their hold is so firm that the iron can not tear itself away, but when present in larger proportion the affinity of the surplus is weaker. This will explain why the tendency to segregation increases with an increase in the content of metalloids. Manganese, copper, and nickel do not come into this class, for their chemical similarity to iron prevents their separation.

Under ordinary circumstances the extent of the purification is so slight that it reduces the content of impurities in any part of the ingot but very little below the average, even though it may result in the serious contamination of the small region which is the last to solidify. This arises from the fact that the surplus is concentrated in a very small quantity of steel. Thus, if the ingot weighs 4000 pounds and contains 0.50 per cent. of carbon, the first 3900 pounds of steel which solidifies should contain 19.5 pounds of carbon, while the last 100 pounds should contain only 0.5 pounds. But if there is a separation of two per cent. of the impurities during the chilling of the 3900 pounds, then this first portion will hold only $19.5 - 0.39 = 19.11$ pounds of carbon, being a content of 0.49 per cent. The last 100 pounds will hold not only its fair proportion of 0.5 pounds of carbon, but also the 0.39 pounds rejected by the earlier solidifying part, and it will therefore contain 0.89 per cent. of carbon. Thus a considerable degree of irregularity can be accounted for without assuming any attempt on the part of the metalloids to isolate themselves from the iron, but by supposing a regular separation of iron in obedience to the fundamental laws of crystallization.

It has been stated that in addition to this simple history of the elimination of iron there is probably a definite process of separation and liquation on the part of the metalloids, which sometimes makes itself known in the formation of a very impure spot in the center of the mass. The exact circumstances under which this occurs to an excessive degree are not known. It is true that slow cooling aids in the work, and

that the most marked cases are found in large masses of metal, but it is also true that both these conditions may exist without any marked irregularity.

The separation of the metalloids probably does not take place to any great extent until the external envelope of the ingot is of a considerable thickness, so that cooling is retarded. When it does occur, the compounds which are formed, being lighter than the mother metal, rise to the top, thereby making the upper part of the ingot somewhat richer in metalloids than the normal. It will also follow that the lower part of the ingot will contain less than the average content of alloyed elements, since whatever excess is in the top must have been taken from the bottom.

For this reason the center of an ingot is not always homogeneous, but this irregularity is considerably lessened in the subsequent working of the steel, particularly if it is heated for a long time, as in the case of large ingots, and also if it undergoes two different heatings and coolings, as in the case of ingots which are first rolled into slabs or blooms, and then reheated to be rolled into plates or angles. During each heating and rolling and cooling there must be a redistribution and equalization of carbon in obedience to the laws of cementation, and since the largest ingots are kept longest in the heating furnaces, it follows that this one condition of larger mass, which is favorable to segregation, is partially self-corrective.

The best-known paper on the irregularity of steel is by Pourcel*, but, unfortunately, it reads like an *ex parte* argument to prove that because some steels exhibit serious irregularities, therefore all steels have the same fault. It is not my intention to err in the opposite direction and attempt to disprove segregation because some steels are homogeneous, but I shall try to show that the facts are not all on the wrong side when viewed from a practical standpoint.

For instance, millions of tons of rails have been made, containing three or four times the amount of carbon that is usually present in structural steel, and consequently presenting ten-

* *Segregation and its Consequences in Ingots of Steel and Iron. Trans. A. I. M. E.*, Vol. XXII, p. 105.

fold the opportunity for segregation, and these rails have also contained more phosphorus than should be found in the best quality of angles, plates, or shapes.

Notwithstanding that no attempt has been made to remove any segregated portion of the ingot, there have been very few, if any, failures of rails which can be ascribed to the liquation of the metalloids. Some rails have been laminated, some have shown hard spots due to insufficient mixing of the recarburizer, some have been too high in phosphorus, carbon, or manganese, some have been overheated, and many more have been broken from lack of a proper roadbed, but segregation has never taken definite shape in the rail manufacture.

I shall try to show that all steels do not exhibit excessive concentration of impurities, that the highly segregated portions of an ingot are often very small isolated areas in the interior of the mass, and that by using a steel of low phosphorus it may safely be assumed that the finished material is practically uniform.

TABLE 49.

Example of Extreme Segregation in Pipe Cavity; from Pourcel, *loc. cit.*

Origin of test.	Composition; per cent.				
	C.	Si.	S.	P.	Mn.
Ladle test	.240	.336	.074	.089	.970
Wall of pipe cavity	.680	.326	.325	.318	1.490
Cake, two inches thick in pipe cavity	1.274	.410	.418	.753	1.080

SEC. 105.—*Examples of segregation in steel castings.*—The most extreme instances of irregularity would naturally be expected in large masses of steel which have been cast in sand, and which have thus cooled very slowly and quietly. In the paper above mentioned, Pourcel states that in the pipe cavity of such a casting a cake of metal was discovered which seemed to be separate from the surrounding walls. The composition of this formation, together with that of the walls of the pipe cavity and of the mother metal, is given in Table 49. It should be noted in this connection that the original metal contained a much higher proportion of phosphorus than should be present in steel castings, so that the conditions were favorable to segregation.

As testimony in an opposite direction, I found no evidence of segregation in a steel roll made by The Pennsylvania Steel Company. This was a plain cylinder 20 inches in diameter, with a total length of 13 feet. A piece four feet long was cut from the top, this amount having been added for a sink-head, and samples of the metal were taken at different depths as the cutting progressed from the outside to the central axis. There were no signs of piping at this point, so that the conditions are not exactly similar to those just cited from Pourcel, but inasmuch as the general practice is to remove all the honeycombed portion of such a casting, the investigation seems to be in the line of practical work. The results of analysis are given in Table 50.

TABLE 50.

Composition of a 20-inch Steel Roll, cast in Sand, made by The Pennsylvania Steel Company, 1893.

Place from which sample was taken.	Composition; per cent.				
	C.	P.	Mn.	S.	Cu.
Two inches from outer surface	.42	.050	.46	.026	.12
Five inches from outer surface	.51	.053	.46	.029	.11
Seven inches from outer surface	.48	.064	.46	.026	.10
Nine inches from outer surface	.47	.053	.46	.026	.14

SEC. 106.—*Examples of segregation in ingots cast in iron molds.*—Under the ordinary system of plate manufacture, as carried out in most American works, an ingot is rolled directly into a plate at one heat, and when the sheets are of ordinarily large size, the weight of each ingot is arranged to give just one plate. It is of great importance to find whether such ingots are uniform throughout, and Table 51 gives the results of investigations which have been made under my supervision.

Under another system of plate rolling, as practiced at some American mills, and more extensively abroad, it is the practice to make larger ingots which are rolled into slabs, these latter being reheated for the plate train. It would naturally be supposed that these slabs would show greater segregation phenomena than are found in ordinary plate ingots, but this assumption is hardly sustained by Table 52, which gives the results obtained by drilling into the axial line of slabs rolled from large ingots, made by The Pennsylvania Steel Works. The points just below the top crop end, and

one-third way down the ingot, are assumed to include the most contaminated region. The concentration shown in these cases probably marks the extent of the action of simple crystallization, while more extreme cases would represent the liquation of small quantities of fusible impure compounds. The content of carbon is not given, for a color determination is worthless when an accurate comparison is to be made, while in the present case the probability of error is unusually great, since the condition of the carbon will not be alike in the center and on the outside of a slab, owing to the difference in the rate of cooling. On the other hand, the estimation by combustion is so tedious that it is not always practicable to make such a large number of analyses.

TABLE 51.
Examples of Segregation in Plate Ingots.

Thickness of ingot in inches.	Part of ingot from which sample was taken.	Composition; per cent.		
		Carbon, by combustion.	Phosphorus.	Sulphur.
10	Preliminary test	und.	.053	.030
	Center, 6 inches from top	.187	.075	.065
	Center, 12 inches from top	.150	.067	.054
	Center, 18 inches from top	.179	.067	.054
	Center, 24 inches from top	.183	.062	.049
	Center, 3 inches from bottom	.145	.058	.044
10	Preliminary test	und.	.064	.051
	Center, 3 inches from top	.247	.061	.044
	Center, 6 inches from top	.364	.088	.097
	Center, 9 inches from top	.340	.078	.069
	Center, 12 inches from top	.295	.078	.069
	Center, 18 inches from top	.272	.081	.064
	Center, 3 inches from bottom	.275	.070	.057
10	Outside, 3 inches from top	.135	.007	.018
	Center, 3 inches from top	.278	.007	.029
	Center, 6 inches from top	.212	.008	.034
	Center, 12 inches from top	.205	.008	.034
	Center, 18 inches from top	.199	.008	.029
	Center, 3 inches from bottom	.159	.007	.017
	Outside, 3 inches from bottom	.164	.007	.020
10	Outside, 3 inches from top	.160	.054	.035
	Center, 3 inches from top	.230	.096	.067
	Center, 6 inches from top	.199	.084	.060
	Center, 9 inches from top	.213	.090	.068
	Center, 12 inches from top	.206	.090	.071
	Center, 3 inches from bottom	.184	.066	.042
	Outside, 3 inches from bottom	.185	.065	.031

SEC. 107.—*Attainment of homogeneity in plates.*—The fact that plates are not homogeneous when rolled from ordinary ingots does not become evident under the ordinary systems of inspection, since, as a general thing, only one piece is taken from the sheet, and this comes from the edge, but it will be

shown by Table 53 that the variations are by no means unimportant. The first instance is taken from Pourcel,* the next three are from Cunningham,† while the last two are from my own investigations.

TABLE 52.

Examples of Segregation in Large Ingots made by The Pennsylvania Steel Company.

The ingots were rolled into a slab, and this was drilled on the center line. Test A is taken just below the top crop end; B is taken one-third way down the ingot, and C from the bottom of the ingot. The carbon in all ingots was between .15 and .25 per cent.

Heat number.	Size of ingot; inches.	Thickness of slab; in.	Origin of test.	Depth at which drillings were taken; in.	Composition; per cent.				Depth at which drillings were taken; in.	Composition; per cent.				Depth at which drillings were taken; in.	Composition; per cent.			
					P.	S.	Mn.	Cu.		P.	S.	Mn.	Cu.		P.	S.	Mn.	Cu.
8188	32x38	5	A	1	.027	.017	.52	und.	2	.041	.026	.57	und.	3	.026	.017	.52	und.
8192	32x38	7	A	1	.019	.021	.56	und.	2	.018	.019	.56	und.	3	.018	.021	.60	und.
10037	32x38	6½	A	1	.058	.037	.77	und.	2	.059	.037	.77	und.	3¼	.060	.040	.85	und.
8201	32x38	6	A	½	.033	.029	.49	und.	1½	.034	.036	.49	und.	2½	.034	.032	.49	und.
			B	½	.037	.033	.49	und.	1½	.038	.038	.48	und.	2½	.046	.047	.49	und.
8202	32x38	6	A	½	.030	.022	.42	und.	1½	.033	.022	.43	und.	2½	.031	.022	.42	und.
			B	½	.039	.023	.43	und.	1½	.038	.026	.42	und.	2½	.040	.026	.42	und.
9584	32x24	10	A	1	.011	.026	.48	.13	3	.015	.036	.50	.14	5	.017	.049	.51	.14
			B	1	.014	.037	.50	.13	3	.014	.038	.51	.14	5	.016	.042	.50	.14
			C	1	.014	.030	.48	.13	3	.013	.032	.48	.12	5	.013	.030	.47	.14
9581	32x24	7	A	1	.010	.021	.42	.10	2	.010	.021	.45	.09	3½	.013	.036	.44	.08
			B	1	.009	.019	.47	.10	2	.010	.020	.42	.11	3½	.012	.035	.43	.10
			C	1	.009	.020	.42	.09	2	.009	.023	.42	.09	3½	.009	.021	.45	.09
8471	32x24	8	A	1	.020	.020	.37	.04	3	.033	.035	.36	.04	4	.037	.039	.39	.05
			B	1	.024	.025	.39	.05	3	.024	.024	.42	.03	4	.024	.024	.39	.04
			C	1	.026	.023	.36	.05	3	.027	.024	.39	.04	4	.026	.023	.38	.05
8478	32x24	7	A	....	.010	.021	.39	.10	2½	.014	.024	.38	.12	3½	.011	.021	.39	.11
			B	1	.012	.022	.37	.12	2½	.012	.026	.38	.12	3½	.017	.042	.38	.11
			C	....	.013	.020	.37	.12	2½	.012	.025	.40	.11	3½	.012	.024	.38	.12
8479	32x24	6	A	....	.013	.022	.35	.11	2	.024	.035	.40	.12	3	.032	.040	.34	.12
			B	....	.019	.023	.36	.12	2	.020	.027	.35	.11	3	.020	.033	.35	.11
			C	....	.015	.020	.36	.10	2	.017	.031	.36	.10	3	.023	.029	.43	.10

The data on heat 11393 were obtained by rolling an ingot on a universal mill into a long plate. The upper third of this

* *Loc. cit.* † *Trans. A. I. M. E.*, Vol. XXIII, pp. 626, *et seq.*

plate was sheared into 16-inch lengths, and tests taken along the center line and the edge. A strip was also cut from the bottom end of the plate in the center and on the edge.

TABLE 53.

Physical and Chemical Properties of Different Portions of Plates Rolled from Ordinary Plate Ingots.

Heat No.	Part of ingot corresponding to the place from which test was taken.	Ultimate strength; lbs. per sq. inch.	Elong. in 8 inches; per cent.	Reduction of area; per cent.	Composition; per cent. C.	P.	S.	Authority.
Not given.	Top, edge	65426	32.0	. . . .	.24	.050	.025	Pourcel.
	Top, center	66848	27.0	. . . .	.32	.100	.061	
	Bottom, edge	59636	33.0	. . . .	.25	.060	.028	
	Bottom, center	59310	32.5	. . . .	.25	.060	.022	
Not given.	Top, edge	53600	30.7	55.9	.15	.021	. . .	C'nningham.
	Top, center	53000	32.0	58.6	.17	.023	. . .	
	Middle, edge	52600	28.2	58.7	.15	.018	. . .	
	Middle, center	55900	28.5	55.0	.16	.022	. . .	
	Bottom, edge	55300	31.5	57.9	.16	.019	. . .	
	Bottom, center	60200	24.5	48.1	.16	.024	. . .	
Not given.	Top, edge	75900	9.5	. . . .	.22	.064	. . .	C'nningham.
	Second piece, edge	69700	20.0	. . . .	.20	.058	. . .	
	Third piece, edge	64200	25.0	. . . .	.18	.034	. . .	
	Fourth piece, edge	65700	25.0	. . . .	.19	.043	. . .	
	Fifth piece, edge	65000	27.0	. . . .	.21	.036	. . .	
	Sixth piece, edge	63700	25.5	. . . .	.19	.038	. . .	
	Seventh piece, edge	66600	23.8	. . . .	.20	.039	. . .	
	Eighth piece, edge	61400	26.0	. . . .	.17	.030	. . .	
	Ninth piece, edge	66600	24.0	. . . .	.19	.040	. . .	
	Bottom	64600	23.8	. . . .	.19	.040	. . .	
Not given.	Edge	59200	22.5	60.8	.08	.077	.040	C'nningham.
	4 inches from edge	66600	24.5	59.1	.08	.151	.063	
	8 inches from edge	67100	23.0	54.7	.09	.141	.085	
	Center	66500	20.0	52.0	.09	.153	.085	
11393	Preliminary test	56000	. . . .	. . . .	. .	.077	.045	Author.
	Top, edge	61600	28.75	45.9	. .	.128	.078	
	Top, center	65420	25.00	44.6	. .	.087	.082	
	Second test, edge	63360	27.00	45.8	. .	.110	.068	
	Second test, center	61490	27.00	44.3	. .	.107	.063	
	Third test, edge	62020	25.25	38.6	. .	.110	.068	
	Third test, center	60330	28.50	53.7	. .	.109	.064	
	Fourth test, edge	59860	26.50	45.8	. .	.098	.056	
	Fourth test, center	59460	29.50	52.5	. .	.098	.045	
	Fifth test, edge	58940	28.50	49.9	. .	.098	.056	
	Fifth test, center	59160	27.50	52.0	. .	.096	.057	
	Sixth test; 1/3 way from top of ingot, edge	59320	27.00	47.5	. .	.097	.055	
	Sixth test; 1/3 way from top of ingot, center	58920	28.75	51.2	. .	.097	.042	
	Bottom, edge	54660	34.75	66.4	. .	.073	.033	
	Bottom, center	53850	29.00	61.0	. .	.070	.031	
10768	Preliminary test	65600	. . . .	. . . .	. .	.059	.049	Author.
	Top, edge	62180	. . . .	. . . .	. .	.088	.057	
	Top, center	63840	. . . .	. . . .	. .	.095	.058	
	Second test, edge	61140	. . . .	. . . .	. .	.075	.048	
	Second test, center	62900	. . . .	. . . .	. .	.083	.045	
	Third test, edge	56090	. . . .	. . . .	. .	.051	.031	
	Third test, center	61280	. . . .	. . . .	. .	.081	.045	
	Fourth test, edge	63480	. . . .	. . . .	. .	.051	.033	
	Fourth test, center	60620	. . . .	. . . .	. .	.084	.050	
	Fifth test, edge	53400	. . . .	. . . .	. .	.051	.032	
	Fifth test, center	61420	. . . .	. . . .	. .	.090	.051	
	Sixth test, edge	56920	. . . .	. . . .	. .	.062	.038	
	Sixth test, center	61000	. . . .	. . . .	. .	.080	.043	
	Bottom, edge	56220	. . . .	. . . .	. .	.065	.042	
	Bottom, center	60220	. . . .	. . . .	. .	.075	.038	

The tests of heat 10768 were cut from a "pitted" plate. The flaws in the bars render worthless any records of elongation, but the chemical results are valuable, while the determinations of tensile strength are probably approximately correct. The ingot was rolled on a shear mill to a thickness of three-quarter inch. The plate was only 112 inches long after trimming, so that the seven tests represent the entire length of the sheet.

Table 54.

Physical and Chemical Properties of Different Portions of Open-Hearth Universal-Mill Plates, Rolled by the Central Iron Works from Pennsylvania Steel Company Slabs.

Note.—Plate No. 1 represents the bottom of the ingot, the others being numbered consecutively toward the top.

Heat No.	No. of plate.	Part of plate.	Elastic limit; pounds per square inch.	Ultimate strength; pounds per square inch.	Elongation in 8 inches; per cent.	Reduction of area; per cent.	Composition; per cent. P.	S.	Mn.
	1	Edge,	33030	54040	29.50	59.1	.066	.040	.39
		Middle,	35880	55000	27.50	61.8	.074	.040	.38
	2	Edge,	33240	54000	29.50	63.8	.068	.044	.36
		Middle,	34870	55540	29.00	61.3	.074	.039	.37
	3	Edge,	32570	53220	31.00	62.5	.068	.040	.37
		Middle,	34670	55420	30.50	62.1	.074	.040	.36
2905 Acid.	4	Edge,	33430	53400	31.25	60.6	.054	.040	.37
		Middle,	35240	56450	30.50	58.4	.074	.045	.35
	5	Edge,	33270	54080	30.75	60.7	.080	.047	.36
		Middle,	34660	56840	33.00	57.1	.088	.052	.35
	6	Edge,	33520	54380	31.00	57.3	.077	.05(	.37
		Middle,	35090	57380	29.25	56.7	.087	.048	.38
	7	Edge,	33150	54120	29.25	59.5	.071	.046	.36
		Middle,	35110	58180	26.25	56.2	.083	.060	.36
	1	Edge,	34050	55360	29.50	63.2	.007	.038	.45
		Middle,	31900	54440	31.50	64.2	.007	.032	.43
	2	Edge,	33580	55350	30.50	59.2	.008	.045	.45
		Middle,	32460	53780	31.75	63.6	.007	.031	.43
9765 Basic.	3	Edge,	33210	56340	28.75	57.8	.007	.040	.45
		Middle,	33170	55240	32.50	63.1	.008	.035	.43
	4	Edge,	33580	56580	30.50	56.5	.007	.036	.45
		Middle,	32550	56020	30.25	60.4	.008	.036	.43
	5	Edge,	33580	56340	28.75	58.2	.007	.042	.46
		Middle,	32800	57240	30.00	58.6	.008	.040	.44

A great deal of this irregularity between different parts of the same plate may be avoided by rolling from a slab as described in the previous section. It would, of course. be

untrue to say that segregation can be avoided by making a larger ingot, or that it can be counteracted by a greater amount of work upon the steel, but it is nevertheless true that a slab will usually give a much more uniform plate.

This will be shown by Table 54, which gives the results obtained by testing the edge and the middle of several universal-mill plates which were made from slabs from the same ingot. A careful record was kept of the position of each slab, and the tests were cut from the top end of each plate. Thus the list of tests from the successive plates gives the same information as if one long slab had been rolled into one plate and had then been cut up for testing.

The segregation in the central axis is shown by a slightly higher content of metalloids, and by a higher tensile strength, but the variations between parts of the same plate, and the variations between different plates, are much less than is shown in Table 53 for plates rolled directly from ingots.

The usual way of testing is to take a strip from a corner of the plate, and Table 55 gives the records so obtained from one-

TABLE 55.

Physical and Chemical Properties of Annealed Bars cut from Plates Rolled from Basic Open-Hearth Slabs, which were cut from different parts of 10-Ton Ingots.

NOTE.—Carbon was determined by color and is therefore unreliable.

Heat number.	Thickness of plate.		Part of ingot from which slab was cut.	Ult. strength; pounds per square inch.	Elastic limit; pounds per square inch.	Elongation in 8 inches; per cent.	Reduction of area; per cent.	Chemical composition; per cent. C.	P.	Mn.	S.
5633. 20-ton heat.	All 1/4 inch.	1st ingot.	Top,	49080	31830	36.75	65.3	.11	.015	.31	.027
				48330	31170	32.00	63.6	.15	.018	.32	.020
				47750	29980	34.50	67.0	.16	.015	.32	.022
				48500	31760	29.50	66.3	.13	.013	.31	.023
				47810	31110	33.00	68.1	.12	.015	.31	.023
				46970	30690	35.00	64.5	.12	.015	.31	.019
			Bottom,	48200	31000	32.50	64.3	.11	.017	.31	.025
			Average,	48091	31077	33.32	65.6	.13	.015	.31	.023
		2d ingot.	Top,	49380	32080	33.00	64.2	.10	.016	.31	.025
				48010	28760	33.00	65.7	.16	.018	.35	.023
				48760	32030	33.75	64.9	.13	.018	.31	.026
				49170	32010	32.00	64.2	.13	.015	.32	.024
				49040	29940	31.75	60.7	.12	.014	.31	.025
				47670	30090	33.00	63.8	.14	.013	.34	.019
			Bottom,	46860	31380	32.50	65.3	.11	.013	.32	.021
			Average,	48413	30899	32.71	64.1	.13	.015	.32	.023

TABLE 55.—Continued.

Heat No.	Thick. of plate.		Part of ingot from which slab was cut.	Ult. strength; pounds per square inch.	Elastic limit; pounds per square inch.	Elongation in 8 in.; per cent.	Reduction of area; per ct.	Chemical composition; per cent.			
								C.	P.	Mn.	S.
5658. 20-ton heat.	All 1/4 inch.	1st ingot.	Top,	51040	32710	31.00	63.8	.13	.014	.48	.014
				51660	33080	30.50	64.1	.12	.014	.46	.021
				51620	32180	33.00	62.8	.13	.018	.42	.025
				51760	32230	32.50	63.3	.14	.011	.44	.024
				51200	31730	31.50	61.1	.13	.017	.41	.024
				50470	32310	32.75	61.8	.12	.006	.45	.023
				50260	33340	32.50	62.6	.10	.012	.45	.020
			Bottom,	50820	32320	33.00	62.1	.10	.016	.47	.021
			Average,	51104	32488	32.09	62.7	.12	.014	.45	.022
		2d ingot.	Top,	52160	32450	32.00	57.0	.14	.009	.45	.025
				52050	31330	32.00	60.7	.12	.017	.46	.024
				52240	32940	33.00	62.6	.11	.018	.47	.023
				50600	33020	31.00	61.0	.11	.013	.46	.016
				50820	32240	32.25	61.2	.12	.014	.44	.022
				50360	32470	32.50	63.5	.13	.005	.45	.023
				50530	32240	32.75	60.0	.12	.013	.46	.016
			Bottom,	49880	31850	34.50	62.8	.11	.012	.46	.016
			Average,	51080	32318	32.50	61.1	.12	.013	.46	.021
8217. 50-ton heat.	All 1/4 inch.	1st ingot.	Top,	52620	32860	31.00	60.2	.16	.019	.44	.032
				52210	36130	32.50	65.0	.16	.019	.43	.032
				50940	31780	32.00	65.7	.14	.016	.44	.028
				50360	30590	28.75	60.0	.15	.019	.44	.029
			Bottom,	50000	31840	31.50	56.4	.14	.016	.44	.025
			Average,	51226	32640	31.15	61.5	.15	.018	.44	.029
		2d ingot.	Top,	51880	36380	32.50	65.5	.14	.017	.42	.029
				53060	30660	28.75	55.2	.15	.024	.44	.033
				52820	35450	27.00	62.2	.16	.021	.44	.031
				52970	32540	31.25	58.9	.15	.017	.44	.030
				52870	31340	31.75	57.9	.15	.019	.44	.032
				50860	30070	32.50	61.4	.15	.019	.44	.029
				50000	33730	35.00	62.7	.14	.017	.44	.029
			Bottom,	50950	31280	35.50	64.5	.14	.016	.44	.025
			Average,	51926	32681	31.78	61.0	.15	.019	.44	.030
8226. 50-ton heat.	All 1/4 inch.	1st ingot.	Top,	54160	38230	26.00	61.5	.13	.039	.32	.050
				53840	38210	27.25	60.1	.13	.033	.28	.058
				54460	38070	28.25	61.4	.12	.038	.32	.050
				51200	35500	31.00	64.0	.13	.023	.28	.028
				53000	38370	30.50	60.9	.12	.031	.37	.051
				51740	37310	31.00	64.9	.11	.031	.31	.047
				52420	37200	27.50	65.2	.11	.030	.29	.046
			Bottom,	53020	37600	31.25	66.3	.12	.033	.29	.050
			Average,	52980	37561	29.09	63.0	.12	.032	.31	.048
		2d ingot.	Top,	54070	38520	27.50	64.4	.12	.036	.34	.058
				54130	38350	30.25	63.8	.13	.037	.31	.053
				51520	36090	26.00	65.6	.13	.036	.31	.057
				52520	38130	30.25	63.8	.11	.031	.31	.048
			Bottom,	52980	37770	31.00	66.0	.12	.031	.29	.044
			Average,	53044	37772	29.00	64.7	.12	.034	.31	.052
		3d ingot.	Top,	54850	37830	30.00	61.9	.13	.037	.26	.056
				54480	36560	28.75	63.8	.13	.035	.30	.048
				53960	38520	29.50	63.3	.12	.034	.32	.047
				53580	37860	28.75	63.8	.12	.033	.32	.045
			Bottom,	53130	37260	25.75	54.3	.12	.031	.32	.047
			Average,	54000	37606	28.55	61.4	.12	.034	.30	.049

Table 55.—Continued.

Heat No.	Thick. of plate.		Part of ingot from which slab was cut.	Ult. strength; pounds per square inch.	Elastic limit; pounds per square inch.	Elongation in 8 in.; per cent.	Reduction of area; per ct.	Chemical composition; per cent.			
								C.	P.	Mn.	S.
823. 50-ton heat.	All 1/4 inch.	1st ingot.	Top.	50270	36[illegible]0	31.75	60.3	.12	.027	.35	.032
				51630	36510	32.00	64.0	.11	.023	.36	.027
				49180	35130	30.75	58.3	.11	.019	.37	.027
				50240	36090	29.25	59.2	.11	.024	.36	.030
			Bottom,	53520	36150	31.00	63.4	.13	.014	.43	.031
			Average,	50968	36152	30.95	61.0	.12	.021	.37	.029
		2d ingot.	Top,	53010	37030	27.50	61.1	.12	.027	.33	.039
				53620	39140	25.75	61.1	.13	.027	.38	.035
				51520	34270	25.50	58.0	.11	.021	.38	.032
				50400	37330	24.75	56.1	.12	.025	.40	.028
			Bottom,	52730	36810	28.50	58.0	.13	.022	.38	.031
			Average,	52256	36916	26.40	58.9	.12	.024	.37	.033
		3d ingot.	Top,	52610	36970	31.25	60.4	.13	.034	.38	.040
				51540	35700	27.00	61.5	.12	.030	.37	.033
				52760	36940	33.00	65.0	.11	.026	.37	.033
				52550	37040	32.00	62.3	.11	.028	.36	.028
			Bottom,	51480	40480	28.75	56.0	.11	.020	.39	.028
			Average,	52188	37426	30.40	61.0	.12	.028	.37	.032
824. 50-ton heat.	All 5/16 inch.	1st ingot.	Top,	56080	35890	30.00	60.0	.19	.025	.48	.030
				55580	34920	28.00	59.0	.14	.019	.46	.024
				54820	34450	31.25	62.0	.13	.019	.46	.023
				54280	35320	31.25	63.0	.14	.023	.46	.025
			Bottom,	54365	34400	30.50	62.2	.17	.022	.47	.021
			Average,	55024	34996	30.20	61.2	.15	.022	.47	.025
		2d ingot.	Top,	55680	35380	31.50	59.2	.11	.024	.49	.027
				55210	34580	29.50	62.3	.12	.024	.48	.027
				54120	35950	31.25	61.2	.14	.021	.47	.026
				53200	34460	31.25	62.7	.12	.020	.46	.020
			Bottom,	54180	34700	31.75	60.9	.13	.021	.49	.021
			Average,	54478	35014	31.05	61.3	.12	.022	.48	.024
		3d ingot.	Top,	54000	35410	31.50	62.8	.14	.020	.46	.021
				55120	36310	29.50	63.8	.13	.025	.48	.027
				54180	35060	30.75	62.9	.17	.024	.45	.028
				53940	34460	30.00	65.4	.14	.019	.46	.022
			Bottom,	53400	33590	31.25	63.6	.15	.019	.46	.020
			Average,	54128	34972	30.60	63.7	.15	.021	.46	.024
		4th ingot.	Top,	55120	34300	30.50	62.6	.16	.021	.47	.027
				54280	34940	29.50	61.9	.15	.024	.47	.025
				53980	35230	28.00	62.3	.13	.022	.54	.041
				52720	33400	32.50	63.8	.14	.021	.46	.024
			Bottom,	54720	34340	31.75	63.2	.14	.023	.46	.025
			Average,	54164	34442	30.45	63.0	.14	.022	.48	.028
		5th ingot.	Top,	53970	35710	30.25	65.3	.16	.023	.48	.024
				54640	34410	33.00	63.9	.16	.021	.47	.024
			Bottom,	53590	33210	32.00	64.9	.12	.019	.46	.021
			Average,	54067	34443	31.75	64.7	.15	.021	.47	.023
		6th ingot.	Top,	53550	35420	31.75	62.6	.15	.022	.48	.023
				54550	36180	32.00	64.6	.12	.021	.49	.026
			Bottom,	55560	37360	28.25	60.C	.15	.024	.49	.022
			Average,	54553	36320	30.67	62.4	.14	.022	.49	.024

TABLE 55.—Continued.

Heat No.	Thick. of plate.		Part of ingot from which slab was cut.	Ult. strength; pounds per square inch.	Elastic limit; pounds per square inch.	Elongation in 8 in.; per cent.	Reduction of area; per ct.	Chemical composition; per cent. C.	P.	Mn.	S.
8235. 50-ton heat.	All 1/4 inch.	1st ingot.	Top,	49880	29740	31.75	58.5	.11	.017	.32	.040
				49150	29680	33.00	63.5	.10	.017	.35	.041
				48190	30030	33.00	57.1	.11	.016	.26	.033
			Bottom,	48190	30270	30.25	60.8	.11	.016	.35	.043
			Average,	48853	29930	32.00	60.0	.11	.017	.32	.039
		2d ingot.	Top,	50480	28570	30.75	61.0	.13	.019	.33	.043
				49030	31880	33.75	62.6	.12	.018	.33	.038
				47740	29930	33.25	63.9	.10	.017	.33	.035
			Bottom,	48310	30430	33.00	64.7	.11	.019	.31	.036
			Average,	48890	30203	32.69	63.1	.12	.018	.33	.038
		3d ingot.	Top,	49630	30410	30.00	64.0	.11	.017	.36	.024
			Bottom,	48910	30510	30.50	63.0	.10	.017	.35	.033
			Average,	49270	30460	30.25	63.5	.10	.017	.36	.029
		4th ingot.	Top,	48440	30460	32.00	65.9	.10	.019	.32	.036
				47600	30530	34.00	57.2	.11	.017	.35	.036
			Bottom,	47260	29850	31.25	58.0	.13	.016	.35	.034
			Average,	47767	30280	32.42	60.4	.11	.017	.34	.035
8236. 50-ton heat.	All 5/16 inch.	1st ingot.	Top,	50660	32710	35.00	64.7	.13	.017	.45	.022
				50860	30480	33.25	63.8	.13	.021	.44	.028
			Bottom,	53860	33710	29.25	58.6	.11	.025	.46	.037
			Average,	51793	32300	32.50	62.4	.12	.021	.45	.029
		2d ingot.	Top,	54080	33970	30.00	59.4	.15	.024	.46	.031
				52680	34100	31.25	63.9	.15	.022	.46	.029
				51520	32140	33.00	61.0	.12	.018	.44	.026
				50750	32840	33.25	64.2	.14	.020	.44	.023
			Bottom,	50280	31760	31.75	65.2	.13	.013	.43	.022
			Average,	51862	32962	31.85	62.7	.14	.019	.45	.026
		3d ingot.	Top,	53440	32440	32.50	60.7	.11	.024	.42	.030
				51620	33400	32.75	65.1	.13	.019	.42	.029
				50660	32650	31.25	61.9	.14	.021	.42	.027
			Bottom,	49260	31460	31.00	65.0	.15	.020	.41	.026
			Average,	51245	32488	31.88	63.2	.13	.021	.42	.028
		4th ingot.	Top,	52060	32460	31.75	64.2	.15	.028	.44	.030
				54260	34450	30.00	59.4	.17	.026	.44	.028
				52880	33450	29.50	62.8	.14	.024	.45	.030
			Bottom,	50890	32090	33.75	61.4	.10	.018	.42	.029
			Average,	52523	33113	31.25	62.0	.14	.024	.44	.029

quarter-inch sheets, which were rolled from basic open-hearth slabs made by The Pennsylvania Steel Company. The ingots from which the slabs were made varied in section from 26″x24″ to 38″x32″, and weighed from 6 to 10 tons each. A record was kept of the part of the ingot from which each slab came, and the corresponding plates were tested both in the natural and in the annealed states.

The table gives only the results on the annealed bars, for by the reheating and cooling the artificial effects of cold finishing were avoided, and all the test-pieces were brought to a common ground of comparison. The plates of any one heat are all of one thickness, the discard of other sizes accounting for the many missing members. In each case the order in the list follows the order in the ingot from top to bottom, and it will be seen that, as a rule, the plates from the top give a slightly higher strength than those from the bottom, but that the variations are unimportant, not being as great as will often be found in different parts of a single plate rolled from an ordinary plate ingot.

TABLE 55A.

Showing that Variations in the Carbon Content in the Test-Pieces given in Table 55 are due to Analytical Errors.

Group A is made up of pieces showing the highest carbons in the heat, and Group B of those showing the lowest.

Heat No.	Group.	Composition; per cent.					
		Original as given in Table 55.			Reworked.		
		Carbon by color.	P.	Mn.	Duplicate determinations by color.		Average of group by combustion.
5633	A	.15 .16	.018 .015	.32 .32	.13 .13	.14 .13	.118
	B	.11	.015	.31	.13	.14	.124
8234	A	.19 .17 .17	.025 .022 .024	.48 .47 .45	.18 .17 .15	.19 .18 .16	.165
	B	.11 .12 .12	.024 .024 .020	.49 .48 .46	.17 .15 .16	.17 .16 .17	.158
8236	A	.15 .17	.028 .026	.44 .44	.14 .14	.14 .15	.150
	B	.11 .10	.024 .018	.42 .42	.13 .14	.13 .14	.149

The carbon determinations in Table 55 are inaccurate since they were made by the color method. The work was performed by men who are regularly engaged in doing nothing else, and without any attempt at extra care, but in order to see whether there really were any such differences in composition as the records would indicate, the samples showing the widest variations in three heats were reworked twice by color and once by combustion; the results are given in Table

55A, and show that the variations in any one heat are in the third place from the decimal point, which is close to the limit of experimental error.

SEC. 108.—*Homogeneity of acid open-hearth rivet and angle steel.*—A very good opportunity of investigating the homogeneity of a heat of steel occurs in the manufacture of rivet rods and angles, where tests may be conveniently taken from many different members. In the case of rivet rods, the test-piece will represent the entire cross section of the ingot, and thus include the segregated portions. Table 56 gives the

TABLE 56.

Tests on Rivet Rounds taken from Different Parts of the Same Heats.

All steels were made by The Pennsylvania Steel Co.

Heat No.	Kind of steel.	Weight of charge.	Diameter of bar.	Composition; per cent.	Ultimate strength; pounds per square inch.		Elastic limit; pounds per square inch.		Elongation in 8 inches; per cent.		Reduction of area; per cent.	
					Natural.	Annealed.	Natural.	Annealed.	Natural.	Annealed.	Natural.	Annealed.
10167.	Acid open-hearth.	110,000 pounds.	¾ inch.	C=.11; P=.053; S=.022; Mn=.34; Cu=und.	61260	55640	43960	34420	31.25	30.00	60.30	66.24
					60950	54760	42430	34840	32.00	29.50	62.73	65.91
					60800	52700	42790	33800	32.00	31.50	65.25	68.88
					60720	55130	43600	34700	31.25	32.50	66.76	67.87
					60210	54600	41160	34040	30.50	30.75	62.60	65.68
					60010	54360	41720	34040	30.50	32.50	66.76	67.74
					59970	54820	40770	33840	30.50	32.00	63.97	64.92
					59710	54340	40900	34320	32.50	32.50	63.43	63.78
					59620	54040	40920	34120	33.00	30.00	57.70	66.39
					59300	54600	40320	34030	34.50	33.00	65.96	68.05
Average,					60260	54500	41860	34220	31.80	31.42	63.55	66.54
10163.	Acid open-hearth.	110,000 pounds.	⅞ inch.	C=.10; P=.011; S=.107; Mn=.40; Cu=.17.	56040	49990	37710	30200	33.25	34.75	65.73	66.70
					56000	50520	37800	30700	35.00	34.25	64.26	69.18
					55520	50520	37890	31750	31.50	35.75	61.86	66.94
					55420	51000	37360	31165	31.75	34.50	62.18	67.97
					55080	49460	36130	30910	33.00	34.75	56.03	68.70
					55040	51170	37980	31475	34.75	34.50	65.48	69.50
					54980	50400	37710	30665	33.00	35.50	59.64	69.68
					54950	50640	37800	31345	31.75	35.00	67.02	69.28
					54860	50520	37980	31970	33.00	35.00	64.09	68.04
					54720	50940	36830	31900	33.75	35.75	55.25	67.85
Average,					55260	50520	37520	31210	33.07	34.97	62.15	68.38
10156.	Acid open-hearth.	110,000 pounds.	⅞ inch.	C=.09; P=.012; S=.021; Mn=.35; Cu=.12.	54000	48870	36230	30990	33.75	33.75	62.30	70.59
					53500	49460	35960	31220	34.50	36.25	63.32	68.27
					53400	48520	35710	31520	33.50	35.50	64.05	69.28
					52390	48290	35880	31190	33.75	32.50	66.49	68.77
					53300	48460	36060	31370	33.75	34.25	61.57	68.14
					52620	49760	35080	32710	33.75	36.25	68.27	67.52
					52620	48640	35080	30490	33.75	36.25	65.29	69.43
					52620	48520	35950	30590	31.25	35.00	62.04	69.49
					51910	49230	36230	32580	32.25	34.50	58.63	67.98
					51900	48410	34840	30350	33.75	33.75	63.72	66.95
Average,					52860	48820	35700	31300	33.40	34.80	63.57	68.64

TABLE 56.—Continued.

Heat No.	Kind of steel.	Weight of charge.	Diameter of bar.	Composition; per cent.	Ultimate strength; pounds per square inch. Natural.	Ultimate strength; pounds per square inch. Annealed.	Elastic limit; pounds per square inch. Natural.	Elastic limit; pounds per square inch. Annealed.	Elongation in 8 inches; per cent. Natural.	Elongation in 8 inches; per cent. Annealed.	Reduction of area; per cent. Natural.	Reduction of area; per cent. Annealed.
10168.	Acid open-hearth.	110,000 pounds.	¾ inch.	C=.12; P=.013; S=.024; Mn=.29; Cu=.27.	55480	49460	37600	29870	32.50	28.75	67.45	65.30
					55480	49940	36670	30350	32.50	31.25	68.22	65.30
					55430	49460	38400	30110	33.25	31.75	68.40	67.70
					55400	49700	37250	31300	30.00	35.00	64.67	69.22
					55160	49700	37950	32730	30.00	32.50	64.97	69.22
					54770	50720	37600	31760	32.50	30.00	69.68	64.62
					54750	50420	38400	32740	33.75	33.75	63.15	61.12
					54690	50010	39120	32470	32.75	32.50	67.35	67.96
					54520	50880	38640	32220	33.00	31.25	67.17	67.25
					54220	49770	38900	32230	33.75	33.75	66.57	69.47
				Av'r'ge	54990	50006	38053	31578	32.40	32.05	66.76	66.72
			⅞ inch.	C=.12; P=.013; S=.024; Mn=.29; Cu=.27.	55000	50230	37710	31950	31.75	33.75	66.31	70.77
					54780	49170	37100	30310	33.75	36.00	62.83	68.77
					54700	50880	36750	31620	32.50	34.00	60.11	66.70
					54180	48820	37450	30840	31.75	35.00	62.30	68.77
					54170	48290	36580	30840	31.25	34.00	67.83	68.77
					53880	48930	36320	30730	31.00	36.00	60.20	68.43
					53770	50520	35610	31670	32.50	34.00	60.02	65.08
					53770	49060	35960	31120	32.75	35.50	65.73	69.76
					52860	50160	35700	31920	33.25	35.50	61.39	69.57
					52600	50640	35360	32400	33.00	35.00	68.49	68.62
	Average,				53970	49670	36450	31340	32.35	34.87	63.52	68.52
1820.	Basic open-hearth.	40,000 pounds.	⅞ inch.	C=.11; P=.02; S=.025; Mn=.31.	48340	. . . . .	33065	. . . . .	34.50	. . . .	71.87	. . . .
					47380	. . . . .	31530	. . . . .	35.00	. . . .	72.05	. . . .
					48450	. . . . .	33650	. . . . .	35.00	. . . .	72.05	. . . .
					48230	. . . . .	31600	. . . . .	37.00	. . . .	74.14	. . . .
					49175	. . . . .	33340	. . . . .	36.25	. . . .	70.09	. . . .
					48560	. . . . .	32760	. . . . .	33.75	. . . .	72.95	. . . .
					47730	. . . . .	33260	. . . . .	35.00	. . . .	74.49	. . . .
					48785	. . . . .	32130	. . . . .	34.00	. . . .	71.80	. . . .
					48640	. . . . .	32935	. . . . .	34.25	. . . .	71.92	. . . .
					49440	. . . . .	33270	. . . . .	34.00	. . . .	71.48	. . . .
					47835	. . . . .	32900	. . . . .	34.00	. . . .	72.72	. . . .
					48050	. . . . .	31920	. . . . .	33.75	. . . .	71.42	. . . .
					48360	. . . . .	32185	. . . . .	36.25	. . . .	74.28	. . . .
					48400	. . . . .	33880	. . . . .	33.75	. . . .	73.64	. . . .
	Average,				48384	. . . . .	32745	. . . .	34.75	. . .	72.49	. . . .

records obtained from several tests taken at random from the piles of rivet rods from five different heats, without any knowledge as to what part of the heat or what part of the ingot the tests came from.

The data on the natural bars are arranged in the order of tensile strength while in parallel columns are given the results obtained by annealing the same bar. Although all the pieces of one heat were annealed at the same time, and with the utmost care to have all conditions uniform, it will be seen that the variations in the strength of the treated bar are entirely independent of the variations in the strength of the

natural bar. This would indicate that the differences are due to irregularities in rolling and to determinative errors rather than to any inherent variations in the character of the metal.

In further proof of this, drillings were taken from the three annealed bars of heat 10168 which showed the highest tensile strength, and from the three which were the weakest. The results of analysis are given in Table 56A.

TABLE 56A.

Composition of Rivet Rods from Heat 10168, which showed the Greatest Differences in the Tensile Strength of the Annealed Bars.

Nature of Sample.	Ultimate strength; pounds per sq. inch.		Composition; per cent.			
	Natural.	Annealed.	C.	P.	S.	Mn.
Preliminary test	52280	. . . . . .	.12	.013	.024	.29
Average of strongest three bars of ⅞ inch diameter . . .	53690	50680	.12	.013	.019	.30
Average of weakest three bars of ⅞ inch diameter . . .	54077	48680	.12	.013	.024	.30

The ingots from which these rivet rods were made measured 16″x20″ in cross section and weighed about two tons each. In the case of angles it is the practice at the Pennsylvania Steel Works to roll a larger ingot than is used elsewhere for the same purpose, the cross section being 24″x26″, and the weight about 5 tons. In order to test the uniformity of the material, the blooms from several such ingots were stamped so as to denote from what part of the ingot each one came, and drillings were taken from the corresponding finished angles.

The results of analysis are given in Table 57, and they show that each ingot was practically uniform throughout. The drillings were taken so as to include the center of the bar, which is the most impure portion. In each case the first bloom in the list is the top of the ingot, and the last is the bottom; the varying number of blooms in the ingots arises from the different weight of the angles to be made.

SEC. 109.--*Homogeneity of high-carbon steels.*—It would naturally be expected that segregation would be most marked in ingots of high-carbon, because such metal remains liquid for a long time. It is found, however, that even under these condi-

tions separation of the impurities does not always occur. This will be shown by Tables 58 and 59, which give the results of certain investigations by The Pennsylvania Steel Company. The data on carbon in Table 58 are of little importance, for a color determination is well-nigh worthless on such high steels.

TABLE 57.

Chemical Composition of Angles, rolled from 26″x24″ Ingots of Acid Open-Hearth Steel, made by The Pennsylvania Steel Company.

NOTE.—The angle from the top of the ingot is marked No. 1, the next No. 2, and so on consecutively to the bottom.

Heat number.	No. of ingot.	No. of angle.	Composition; per cent. S.	P.	Mn.	No. of ingot.	No. of angle.	Composition; per cent. S.	P.	Mn.	No. of ingot.	No. of angle.	Composition; per cent. S.	P.	Mn.	No. of ingot.	No. of angle.	Composition; per cent. S.	P.	Mn.
11391	A	1	.043	.063	.41	B	1	.033	.069	.41	C	1	.045	.065	.40	D	1	.044	.060	.41
		2	.050	.066	.39		2	.039	.068	.41		2	.011	.065	.39		2	.033	.064	.41
		3	.043	.063	.40		3	.036	.063	.42		3	.012	.058	.40		3	.038	.058	.40
		4	.011	.061	.40		4	.045	.068	.41		4	.038	.058	.43		4	.037	.062	.40
		5	.042	.061	.42		5	.031	.051	.42		5	.039	.057	.40		5	.040	.060	.42
		6	.036	.061	.39		6	.035	.065	.42		6	.036	.060	.39		6	.033	.062	.41
		7	.033	.060	.40		7	.033	.060	.42		...	...	...	...		7	.033	.058	.41
		8	.033	.056	.41		...	...	...	...		...	...	...	...		...	...	...	...
	E	1	.032	.049	.41	F	1	.054	.076	.40	G	1	.039	.081	.39	H	1	.039	.068	.40
		2	.039	.062	.40		2	.041	.062	.41		2	.039	.067	.39		2	.039	.064	.35
		3	.039	.063	.40		3	.039	.059	.37		3	.039	.060	.40		3	.036	.059	.38
		4	.039	.062	.41		4	.041	.058	.41		4	.037	.061	.38		4	.034	.057	.39
		5	.039	.062	.41		5	.039	.058	.42		5	.036	.060	.38		5	.034	.057	.38
		6	.041	.054	.41		...	...	...	...		6	.033	.056	.38		6	.037	.064	.39
		7	.037	.060	.42		...	...	...	...		7	.033	.055	.41		...	...	...	...
10867	A	1	.052	.080	...	B	1	.034	.081	...	C	1	.051	.074	...		...	...	...	...
		2	.049	.064	...		2	.041	.073	...		2	.048	.067	...		...	...	...	...
		3	.044	.076	...		3	.040	.071	...		3	.040	.061	...		...	...	...	...
		4	.052	.059	...		4	.041	.070	...		4	.010	.065	...		...	...	...	...
		5	.040	.069	...		5	.040	.069	...		5	.040	.061	...		...	...	...	...
		6	.025	.070	...		6	.042	.069	...		6	.033	.068	...		...	...	...	...
		7	.033	.068	...		7	.040	.067	...		7	.040	.069	...		...	...	...	...
		8	.042	.068	...		8	.042	.063	...		8	.032	.067	...		...	...	...	...
		9	.038	.067	...		9	.036	.062	...		9	.036	.068	...		...	...	...	...
		10	.039	.066	...		10	.034	.033	...		...	...	...	...		...	...	...	...
		11	...	...	...		...	...	...	...		...	...	...	...		...	...	...	...

The determinations of carbon in Table 59 are made by combustion and are accurate, and they show a considerable variation in the distribution of this element; this might be expected when such a large proportion is present, and its

hold upon the iron correspondingly less firm. The sulphur and phosphorus are very regular, the variations in the purer metal being almost within the limits of error. In the ingot of medium phosphorus, the percentage of variation is no more than in the others, but the actual range is greater. Although this would follow naturally, it is possible to show, by an incident which happened under my own observation, that concentration does not always occur, even in the case of impure steels.

TABLE 58.

Distribution of Elements in a High-Carbon, Low-Phosphorus Open-Hearth Ingot, 14 inches square, 63 inches long.

NOTE.—Made by The Pennsylvania Steel Company. Carbon was determined by color, and is, therefore, only approximate.

Part of the ingot from which test was taken.	Depth from which drillings were taken; in inches.	Composition; per cent.					
		C.	P.	Mn.	Average.		
					C.	P.	Mn.
Four inches from bottom,	2 4 6 7	.79 .78 .79 .72	.013 .015 .013 .012	.20 .20 .19 .19	.77	.013	.20
Fifteen inches from bottom,	2 4 6 7	.77 .87 .84 .78	.011 .015 .011 .011	.20 .20 .20 .19	.81	.012	.20
Twenty-six inches from bottom,	2 4 6 7	.80 .89 .85 .81	.012 .014 .014 .009	.18 .21 .21 .20	.84	.012	.20
Thirty-seven inches from bottom,	2 4 6 7	.77 .90 .89 .83	.011 .014 .015 .012	.20 .21 .20 .20	.85	.013	.20
Forty-eight inches from bottom; all above this would be cut off as scrap when the ingot is rolled,	2 4 6 7	.79 .91 .89 .94	.011 .014 .016 .014	.21 .20 .19 .21	.88	.014	.20
Four inches from top,	2 4 6 7	.74 .90 .95 1.06	.010 .016 .017 .023	.21 .21 .21 .21	.91	.016	.21

A 50-ton acid open-hearth charge had been made containing .46 per cent. of carbon, together with unusually high manganese, phosphorus, and silicon. The ingots had a cross section of 16″x20″, and weighed about 4000 pounds each. In loading them, one fell over and "bled" at the top. The amount of liquid metal thus lost did not exceed 25 pounds, although the cavity was completely emptied, so that if segre-

gation existed to any considerable extent it should appear in this metal which remained liquid to the last. Table 60 will, however, show that very little segregation had taken place.

TABLE 59.

Distribution of Elements in 7-inch Square Blooms Rolled from High-Carbon, Open-Hearth Ingots, 14 Inches Square.

A slice was cut crosswise from the rolled bloom at different places and drillings taken from the *center* of this slice, corresponding to the center of the ingot.

Kind of ingot.	Place from which slice was taken.	Composition; per cent.				
		C by comb.	P.	Mn	S.	Si.
Low-phosphorus ingot.	Ladle test	.984	.013	.09	.022	.12
	Top of ingot after cutting off 20 per cent. as scrap	.941	.015	.11	.012	.09
	One-fourth way down the ingot	.990	.019	.11	.010	.10
	One-half way down the ingot	.991	.017	.11	.012	.09
	Three-quarters way down the ingot	.982	.020	.11	.010	.11
	Bottom of ingot	1.012	.016	.11	.010	.11
Medium-phosphorus ingot.	Ladle test	1.440	.050	.28	.016	.12
	Top of ingot after cutting off 20 per cent. as scrap	1.205	.064	.28	.015	.16
	One-fourth way down the ingot	1.430	.059	.27	.015	.12
	One-half way down the ingot	1.443	.051	.27	.013	.12
	Three-quarters way down the ingot	1.400	.053	.27	.014	.13
	Bottom of ingot	1.459	.055	.27	.012	.12
Low-phosphorus ingot.	Ladle test	.913	.024	.13	.019	. .
	Top of ingot after cutting off 20 per cent. as scrap	.925	.021	.13	.018	. .
	One-fourth way down the ingot	.965	.022	.14	.018	. .
	One-half way down the ingot	.948	.021	.13	.020	. .
	Three-quarters way down the ingot	.956	.025	.13	.021	. .
	Bottom of ingot	.943	.021	.13	.021	. .

SEC. 110.—*Homogeneity of acid open-hearth nickel steel.*—It is the current impression among manufacturers of nickel steel that the presence of this element prevents segregation. In order to have some evidence upon this point, an investigation was conducted on an ingot of nickel steel made by The Pennsylvania Steel Company. The cross section of the ingot was 18″x20″, and the weight about 5500 pounds. This was rolled into a piece 16 inches wide, 5 inches thick, and 20 feet long, and cut into five slabs. The top slab was rolled into a three-eighth-inch universal plate, the second slab into a three-eighth-inch sheared plate, the third slab into a half-inch universal plate, the fourth slab into a half-inch sheared plate, and the fifth slab was hammered into a bloom and then rolled into 6″x4″ angles.

Each end of each slab was marked so as to note whether it was toward the top or bottom of the ingot, and the location

of each test-piece in each plate was kept of record. Table 61 gives the physical and chemical results obtained from the different strips, while the diagram immediately below the table represents the entire length of the original piece produced by rolling the 18"x20" ingot to a section of 16"x5". The numbers on this diagram correspond to the numbers of

TABLE 60.

Composition of the Liquid Interior of an Ingot as Compared with the Ladle Test of the Same Charge.

Origin of sample.	Composition; per cent.				
	Carbon by combustion	P.	S.	Mn.	Si.
Metal from interior	.480	.095	.047	0.95	und.
Ladle test	.461	.091	.034	1.13	.12

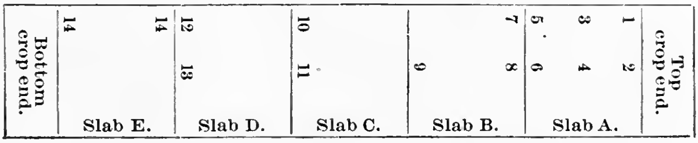
TABLE 61.

Homogeneity of Acid Open-Hearth Nickel Steel.

Size of ingot, 18"x20"; made by The Pennsylvania Steel Company. Composition of preliminary test, per cent.: C, .24; Mn, .78; P, .032; S, .027.

Slab mark.	Shape into which slab was rolled.	No. of test.	Composition; per cent.				Ultimate strength; pounds per square inch.	Elastic limit; lbs. per square inch.	Elongation in 8 inches; per cent.	Elongation in 2 inches; per cent.	Reduction of area; per cent.
			Ni.	P.	Mn.	S.					
A	⅜-inch universal mill plate.	1	3.22	.038	0.78	.036	86480	59000	19.25	37.00	47.8
		2	3.21	.040	0.80	.046	88500	59500	20.50	36.00	39.1
		3	3.31	.035	0.78	.034	85140	59240	21.75	39.00	54.2
		4	3.24	.039	0.78	.036	88700	58100	19.75	34.50	38.6
		5	3.22	.031	0.77	.028	84080	57320	21.25	40.00	53.1
		6	3.29	.037	0.77	.026	85400	59410	19.75	38.00	51.5
B	⅜-inch sheared plate.	7	3.27	.035	0.77	.034	84440	58800	19.50	37.00	48.8
		8	3.29	.039	0.77	.037	86680	59640	17.00	31.50	42.8
		9	3.27	.037	0.78	.038	86520	59560	20.50	37.00	52.6
C	½-inch universal mill plate.	10	3.22	.037	0.77	.032	86200	58260	21.00	40.00	54.1
		11	3.22	.037	0.78	.032	85660	56760	22.00	42.00	53.1
D	½-inch sheared plate.	12	3.21	.035	0.77	.034	85180	56800	19.00	34.50	50.2
		13	3.21	.035	0.78	.033	84020	57600	20.50	39.00	52.2
E	Angles.	14	3.25	.038	0.77	.033	86960	58550	21.75	39.67	50.5

NOTE.—The following diagram shows the parts of the ingot which correspond to the places in the plates from which the tests, given in the third column of above table, were taken.



the test-pieces in the table, and serve to mark the exact place in the ingot from which the corresponding test-piece was derived.

It will be seen that there are evidences of segregation, both in a slightly higher tensile strength and in higher phosphorus and sulphur, in the center of the ingot near the top, but the differences are unimportant, and in view of the fact that the carbon in the steel was .24 per cent., there seems to be good ground for the assumption that nickel prevents the separation of the metalloids. It has not prevented it altogether, however, and it is not probable that any other agent will ever be found competent for this task.

The burden of the testimony given in this chapter is to the effect that segregation is an ever-present factor; that the extent of the concentration bears a certain relation to the proportion of impurities that are present; that manganese, copper, and nickel, do not segregate to any extent, but that certain portions of the finished material will contain a higher percentage of carbon, phosphorus, and sulphur than will be found in the tests cut from the edge of plates and bars, or than will be shown by an analysis of the preliminary test. It is also indicated that a degree of uniformity, sufficient for practical needs, may be expected if the initial metal be low in phosphorus and sulphur.

CHAPTER XIV.

INFLUENCE OF HOT WORKING ON STEEL.

SECTION 111.—*Effect of thickness upon the physical properties.*—One of the fundamental difficulties in writing specifications is to decide the nature of the test-piece to be required, inasmuch as the strength and ductility will vary in pieces of different thickness, while the results will not be alike in tests cut from different structural shapes, like plates, angles, and rounds, even though they be rolled from the same steel. From one point of view each piece of metal throughout a bridge should be of exactly the same strength per unit of section without regard to its thickness; but in taking this as a basis a serious trouble is encountered. Suppose, for instance, that a metal is required running between 56000 and 64000 pounds per square inch, and a charge is made which in three-eighth-inch plate gives 57000 pounds. If this steel be rolled into seven-eighth-inch angles, or into one-inch plate, or into two-inch rounds, it is quite probable that these will run below the allowable minimum. On the other hand, if the steel gives 62000 pounds in a preliminary test, the larger sections will give proper results, while one-quarter-inch plate will be too high in ultimate strength.

Where a structure is to be made of large quantities of very large or very small sections, it is well to specify that the test shall be made on the special thicknesses needed, but in ordinary cases it seems absurd to the practical mind that a heat of steel can be perfectly suitable for one size and unsuitable for another. It was the custom in the past for inspectors to recognize the situation and make tests from the usual sizes, with a full knowledge that thicker and thinner members would give different results, but in later practice there is a

growing tendency to test each separate thickness, a change which has been the cause of great expense to the manufacturer. Provisions to cover this point should be incorporated into contracts and a certain definite allowance made so that manufacturers would be obliged to put sufficient work on large members to render them of proper structure, and would at the same time be prevented from finishing thin pieces at too low a temperature.

There is often a confusion of terms in considering the effect of work as represented by a large percentage of reduction from the ingot, and the effect of finishing at a low temperature. This is found most often in the case of plates, for it has been quite a general practice to roll these direct from the ingot in one heat. In order that a piece shall be finished hot enough under this practice, there has been a standing temptation to use a thin ingot; but, on the other hand, it has been almost universally shown that the best results are obtained when a large amount of work is put upon the piece during rolling.

SEC. 112.—*Discussion of Riley's investigations on the effect of work.*—The truth of this last statement was disputed by Riley,* who tabulated the results of testing different thicknesses of plate when rolled from ingots of varying section. In all cases the ingot was either hammered or cogged to a slab and this was reheated before finishing into a plate. His analysis of the records consisted in picking out individual cases and showing that the small ingots gave some results which were equal to those from the large ones, but this method of comparison must be recognized as entirely unworthy of the subject. It is true that the number of tests is very small, and it would not be surprising if the accidental variations in the double working should produce anomalous results; but even taking these very data and making comparisons by the proper system of averages, it will be found that they tell a story exactly opposite from the conclusions formulated by Mr. Riley. In Tables 62 and 63 such figures are presented.

In the comparison of the different thicknesses in Table 62 the thinner plates give much better results, the one-half-inch

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* *Some Investigations as to the Effects of Different Methods of Treatment of Mild Steel in the Manufacture of Plates. Journal I. and S. I.*, Vol. I, 1887, p. 121.

plate showing an increased ductility in spite of its greater strength. The one-quarter-inch plates are somewhat lower in elongation and two and one-half per cent. better in reduction of area than the one-inch plates, but they possess 7600 pounds more strength, so that less ductility should be expected. This statement is open to criticism, as no account is taken of the effect of variation in the dimensions of the test-piece, but Table 63, which is free from this error, proves that the plates made from the large sizes have a higher tensile strength and greater ductility.

TABLE 62.

Average Physical Results on Different Thicknesses of Steel Plates Without Regard to Size of Ingots; There Being an Equal Number of Plates of Each Thickness Rolled from Each Sized Ingot.*

Thickness of plate.	Ultimate strength; lbs. per square in.	Elongation in 8 inches; per cent.	Reduction of area; per cent.	Annealed, ultimate strength; pounds per square inch.
One inch . . .	62037	24.40	40.20	59416
One-half inch.	64534	24.71	44.85	61018
One-quarter in.	69642	22.35	42.68	62989

TABLE 63.

Average Physical Results on Plates from Different-Sized Ingots Without Regard to Thickness of Plate; There Being the Same Number of Each Thickness Rolled from a Given Size.†

Size of ingot; in inches.	Thickness of slab in inches.	Ultimate strength; lbs. per square inch.	Elongation in 8 inches; per cent.	Reduction of area; per cent.	Annealed ultimate strength; pounds per square inch.
24x15	8	66155	24.14	45.79	62197
14x14	8	65296	23.91	44.13	62571
18x12	8	65128	23.77	41.38	60461
18x12	4	65520	23.68	40.00	60461
12x 6	4	64923	23.68	41.58	60013

Thus these experiments which were heralded as upsetting current beliefs are found to vindicate them; they do prove that in some cases very good results may be obtained by skillful manipulation under a bad system; but manufacturers have long since learned that a large amount of reduction is essential to secure reliable results in regular practice, and no short series of tests can upset this well-established fact.

*† From data in *Journal I. and S. I.*, Vol. I., 1887, p. 121, *et seq.*

SEC. 113.—*Amount of work necessary to obtain good results.*— In America it has not been the general custom in making large plates to take two heats on the steel, but it will be evident that when a heavy ingot is rolled down to a thin plate there will either be an enormous strain on the machinery or a cold-finished piece. The effect of this cold finish is very irregular, for the edges and ends are most seriously affected, and the plate is in a bad physical condition.

To avoid, on the one hand, the objectionable cold finish, and to gain on the other the advantage of sufficient work, the practice has been gaining ground of rolling a large ingot into a slab which is proportioned to the plate to be made. By this method all thicknesses may be finished at about the same temperature without respect to the total amount of work put upon the ingot. It is difficult to say just what the intermediate size should be for a given plate. Theoretically it would seem immaterial whether a 15-inch ingot is cogged to 8 inches and rolled to one-half inch, or whether it is cogged to 4 inches and rolled to the same thickness. The experiments of Mr. Riley point the same way, but they are far from being comprehensive. If a slab 4 inches thick is not heated to a full heat the plate may be finished at the same temperature as one of the same gauge rolled from a hotter slab of twice the thickness, but in regular practice the thin slabs are sometimes heated hotter than the thick ones, and consequently will be finished at a higher temperature. If carried too far this produces a coarser structure and an inferior metal, so that it is best to proportion the thickness of the slab to the thickness of the plate. The exact relation is of little importance as long as the reduction is sufficient, for in this matter the old adage is strictly applicable: "enough is as good as a feast." This will be shown by Tables 64 and 65, which investigate the effect of work on billets made from ingots 16 inches square and which thus had an all-sufficient reduction to begin with.

It will be found from a detailed comparison of these tables that there is little difference between the bars of the same thickness, even though rolled from different-sized billets. There is a gain in ultimate strength as the thickness decreases, this being most marked in the cold-finished bars, but the differences are not very marked except in the case of

the one-eighth inch. The elastic limit follows the same law, but it is raised more than the ultimate as the bar gets thinner. The elongation varies irregularly, but, as a rule, it remains unaffected except in the one-eighth inch, where it is lowered to some extent. The reduction of area is also irregular, but it seems to be independent of the thickness even in the thinnest plate. The conclusion seems justifiable that if the billets have already received sufficient work, the good condition caused thereby is not destroyed by reheating, since bars

TABLE 64.

Influence of Thickness of Test-Piece on the Physical Properties when the Percentage of Reduction in Rolling is Constant for all Thicknesses; the Finished Bars in each Case having a Sectional Area of About 8 Per Cent. of the Billet.

Heat number.	Size of billet; in inches.	Size of bar; in inches.	Ultimate strength; lbs. per sq. inch.		Elastic limit; pounds per square inch.		Elongation in 8 inches; per cent.		Reduction of area; per cent.	
			Finished at usual temperature.	Finished at dull red heat.	Finished at usual temperature.	Finished at dull red heat.	Finished at usual temperature.	Finished at dull red heat.	Finished at usual temperature.	Finished at dull red heat.
4605	4x4	2x5/8	51640	51280	33440	35380	37.50	29.50	60.1	50.9
	3 5/8x3 5/8	2x1/2	51120	52340	32650	35410	32.50	33.75	56.4	55.6
	3x3	2x3/8	50850	51970	35700	37860	32.50	30.00	60.8	58.9
	2 1/2x2 1/2	2x1/4	53320	53200	37360	41400	31.25	31.50	61.0	66.2
	2x1 5/8	2x1/8	....	58850	....	50620	....	19.75	...	58.4
9227	4x4	2x5/8	59540	60160	37050	39840	35.00	31.00	60.0	57.4
	3 5/8x3 5/8	2x1/2	59730	60490	38100	40490	29.75	32.50	56.4	55.1
	3x3	2x3/8	60950	61390	42110	42090	30.00	30.50	60.0	55.9
	2 1/2x2 1/2	2x1/4	62350	62700	43070	46630	27.50	28.75	60.7	63.3
	2x1 5/8	2x1/8	65130	67470	52180	57830	26.25	23.75	58.9	67.5
1509	4x4	2x5/8	67860	68140	42850	44050	25.00	24.25	40.8	43.9
	3 5/8x3 5/8	2x1/2	67550	68040	43190	45560	26.25	28.25	46.1	46.6
	3x3	2x3/8	67470	68300	44090	46610	26.25	23.25	53.2	50.3
1440	4x4	2x5/8	72840	73260	47080	49160	25.00	24.00	40.7	40.8
	3 5/8x3 5/8	2x1/2	71230	73510	46010	50830	26.25	25.00	40.5	43.5
	3x3	2x3/8	72950	73710	48760	50540	26.25	22.00	52.1	43.1
	2 1/2x2 1/2	2x1/4	73620	75650	51550	58280	26.25	26.75	45.9	52.1
	2x1 5/8	2x1/8	78560	79260	58140	63820	22.75	25.25	52.0	50.4

rolled from them reach their standard level of quality with only a reasonable degree of reduction, as proven by the fact that further work gives no decided improvement. But it is also certain, as shown by all experience, that no harm can be done by increased work, and that there is a slight gain in the long run provided the finishing temperature remains constant.

SEC. 114.—*Experiments on forgings.*—The persistency of a proper structure even through subsequent heating may be seen in Table 66, which gives the results obtained from a series of forged billets. The original bloom was 6 inches square, being rolled from an ingot 18″x20″. From this bloom several short pieces were cut and treated in the following ways:

TABLE 65.

Influence of Thickness of Bar upon the Physical Properties when all Pieces are Rolled from Billets Three Inches Square.

Heat number.	Size of bar; in inches.	Ultimate strength; lbs. per square inch.		Elastic limit; pounds per square inch.		Elongation in 8 inches; per cent.		Reduction of area; per cent.	
		Finished at usual temperature.	Finished at dull red heat.	Finished at usual temperature.	Finished at dull red heat.	Finished at usual temperature.	Finished at dull red heat.	Finished at usual temperature.	Finished at dull red heat.
4605	2x5/8	51370	50960	32860	33760	34.50	32.75	59.6	56.7
	2x1/2	51070	52430	33200	36050	31.50	30.00	59.2	57.2
	2x3/8	50850	51970	35700	37860	32.50	30.00	60.8	58.9
	2x1/4	52960	52280	36220	40040	31.25	32.50	63.2	68.3
	2x1/8	55560	55000	47380	42500	30.00	29.00	53.2	60.4
9227	2x5/8	59690	60190	37000	40130	35.00	30.00	55.4	58.7
	2x1/2	60350	60510	38560	40470	29.50	32.50	58.8	61.7
	2x3/8	60950	61390	42110	42090	30.00	30.50	60.0	55.9
	2x1/4	62230	63970	42600	49200	25.75	29.25	55.9	61.9
	2x1/8	66340	68130	49860	56180	27.50	24.00	56.6	65.7
1509	2x5/8	65600	67090	40980	45830	29.50	25.50	50.9	44.8
	2x1/2	67310	67660	43090	45170	26.25	25.50	47.1	46.2
	2x3/8	67470	68300	44090	46610	26.25	23.00	53.2	50.3
	2x1/4	69210	70200	47950	53680	26.50	25.25	54.1	56.9
	2x1/8	72100	77460	54060	64430	27.75	15.25	55.0	48.2
1440	2x5/8	72440	74060	46440	49480	27.50	24.00	45.7	42.0
	2x1/2	72570	68150	46200	45990	27.25	28.50	47.3	53.4
	2x3/8	72950	73710	48760	50540	26.25	22.00	52.1	43.1
	2x1/4	75620	71260	51160	54660	25.00	27.25	53.5	49.4
	2x1/8	77500	80240	60920	69360	26.00	18.50	46.8	53.6

A was not reheated, but a test-piece was cut from it as a standard of comparison.

B was heated to a full working heat and cooled without hammering.

C was hammered to 5 inches square in one heat.

D was hammered to 4 inches square in one heat.

E was hammered to 3 inches square in one heat.

F was hammered to 2 inches square in one heat.

G was hammered to 2 inches square in one heat from the annealed bar *B* and was finished at a cherry red heat.

H was hammered to 5 inches square, then reheated and hammered to 4 inches.

I was hammered to 4 inches square, then reheated and hammered to 3 inches.

K was hammered to 3 inches square, then reheated and hammered to 2 inches.

L was hammered to 5 inches square, then overheated and cooled without hammering.

M was made by reheating the burned piece *L* and hammering to 2 inches square in one heat, being finished at a cherry red heat.

All the pieces were worked under a 4-ton double-acting hammer, and the test-bars were cut from the corner of the billet and pulled in a length of 2 inches.

TABLE 66.

Effect of Hammering Rolled Acid Open-Hearth Steel.

NOTE.—Chemical composition in per cent. was C, .40; Mn, .86; P, .037; S, .046.

Mark on bar.	Size of billet in inches; being the measure of the side of the square.	Elastic limit; pounds per square inch.	Ultimate strength; pounds per square inch.	Elongation in 2 inches; per cent. in a section ¾ inch in diameter.	Reduction of area; per cent.	Elastic ratio; per cent.	Remarks.
A	6	54460	89240	29.00	41.2	61.0	Finished at dull yellow.
B	6	41500	88660	28.00	42.2	46.8	Annealed at bright yellow.
C	5	50800	89070	26.50	38.0	57.0	Finished at dull yellow.
D	4	55240	87300	25.50	37.0	63.3	Finished at dull yellow.
E	3	51170	86450	27.50	39.3	59.2	Finished at dull yellow.
F	2	51830	89280	28.00	41.8	58.1	Finished at dull yellow.
G	2	57140	92400	28.00	42.0	61.8	Finished at cherry red.
H	4	45620	89900	27.00	38.9	50.8	Finished at dull yellow.
I	3	47830	88800	25.00	34.3	53.9	Finished at dull yellow.
K	2	51000	88760	27.50	42.7	57.5	Finished at dull yellow.
L	5	54020	86400	7.50	5.8	62.5	Annealed at white heat.
M	2	54700	93360	24.50	34.8	58.6	Finished at cherry red.

It is quite evident that the pieces which were heated twice, and which received only one inch of reduction after the second heating, must have been finished hotter, as well as have received less work after a full heat, but in spite of these differences in amount of work and temperature it is clear that the bars are practically uniform in strength and ductility, showing that the steel was in thoroughly good condition originally, and that proper heating did no harm when followed by a fair amount of work.

The ultimate strength is fairly uniform save in the case of the two bars which were finished at a cherry red heat. The elastic ratio varies in much greater measure, but the results are not regular since, in some cases, as in *K*, a high ratio accompanies heavy reduction under the hammer, while in others, as in *D*, it appears in bars which have received very little work.

The original bar *A* shows a high ratio, but this was finished at a low heat. In the annealed bar *B* the ratio drops very much, but the "burned" bloom *L* shows almost as high an elastic strength as the original steel. In the bar *M*, which should be compared with the bar *G*, it is shown that reheating and hammering will do very much toward restoring a piece of burned steel to its original condition, although it is doubtful whether it ever can make of it a thoroughly reliable material.

TABLE 67.

Comparative Physical Properties of Test-Pieces of Bessemer Steel Cut from Thick and Thin Angles of Large and Small Sizes.

Each figure is an average of 50 bars.

Thickness of angle; inches.	Elastic limit; lbs. per sq. in.		Ult. strength; lbs. per sq. in.		Elastic ratio; per cent.		Elongation in 8 in.; per cent.		Reduction of area; per cent.	
	Large sizes.	Small sizes.	Large sizes.	Small sizes.	Large sizes.	Small sizes.	Large sizes.	Small sizes.	Large sizes.	Small sizes.
$\frac{5}{16}$	....	44158	....	61252	....	72.09	....	27.55	....	56.79
$\frac{3}{8}$	43002	43090	60097	60629	71.55	71.07	28.13	28.55	58.23	54.80
$\frac{7}{16}$	43637	43128	60019	60239	72.70	71.59	28.16	28.52	57.59	57.53
$\frac{1}{2}$	41671	41634	60120	59151	69.31	70.38	28.58	29.24	55.17	56.96
$\frac{9}{16}$	41080	41836	59467	59750	69.08	70.02	28.65	28.74	55.30	57.59
$\frac{5}{8}$	40391	40944	59360	59084	68.04	69.30	29.03	29.38	53.43	56.07
$\frac{3}{4}$	38867	....	58267	....	66.70	....	28.37	....	51.63	....

SEC. 115.—*Tests on Pennsylvania Steel Company angles of different thicknesses.*—The fact that there is very little difference between thick and thin pieces, provided the work has been sufficient in both cases, is shown by Table 67. This was constructed by taking at random from the records of The Pennsylvania Steel Company the tests on fifty bars of small angles and fifty bars of large angles of each different thickness, of common Bessemer steel, running from .07 to .10 per cent. of phosphorus.

For making the 6″x6″ angles, a bloom 8″x9½″ was rolled from a 16″x20″ ingot, but all other sizes were made from a 7½-inch square bloom which was cogged from a 16″x16″ ingot. The term "small" angles includes 4½″x3″, 4″x4″, and all smaller sizes down to and including 3″x3″; while the "large" embraces from 5″x3″ to 6″x6″, inclusive. The finished area of the smaller bars is such a small part of the original bloom that the reduction may be considered uniform for them all, thus giving a fairly valid basis of comparison for the different thicknesses, while the columns "large" and "small" should show the effect of a varying amount of work on a piece of given thickness.

It will be noted that the small-sized angles give slightly better results on elongation, but the difference is trifling, while in neither the elastic ratio nor the reduction of area is there any marked superiority. The results indicate that when the amount of work is large, the exact percentage is of little consequence.

The ultimate strength decreases in the thicker angles, but it is not proven that the variation is due entirely to the thickness, for it may be that the heats which were rolled into thick sizes did happen to be of lower strength, but as all the heats were made in the same way, and as both large and small sizes follow the same law, and as each group includes fifty bars, it seems probable that the gradation represents in some measure the effect of different amounts of work on the material.

SEC. 116.—*Comparison of the strength of angles with that of the preliminary test-piece.*—That the thin angles will give a higher strength is proven quite conclusively by Table 68, which gives in parallel columns the tests on the finished angles from acid open-hearth heats, and the results obtained from bars rolled from 6-inch square ingots of the same charges. It matters not whether this preliminary test really represents the true value of the steel, for it may reasonably be assumed that it will give a regular basis of comparison, so that the differences between the results on this standard and on the various thicknesses will be the measure of the effect of rolling.

It is shown that for an increase of one-eighth of an inch

in thickness there is a diminution in strength of 700 pounds per square inch. It is, perhaps, as close an agreement as could be expected when we find that in Table 67 the difference on the large sizes between the three-eighth inch and three-quarter-inch angles was 1830 pounds per square inch, or 610 pounds to every one-eighth in thickness, while on the smaller sizes it is 2168 pounds from five-sixteenth inch to five-eighth inch, or 434 pounds to every eighth, being an average of 522 pounds for both large and small sizes.

TABLE 68.

Comparison of Ultimate Strength of Bars Rolled from Test Ingots Six Inches Square, and Test-Pieces Cut from Angles of Different Thicknesses Rolled from the Same Heats.

Thickness of angle; in inches.	Number of heats represented.	Elastic limit; lbs. per square inch.			Ultimate strength; lbs. per square inch.			Elastic ratio; per cent.	
		Bar from test ingot.	Bar from angle.	Loss of strength in angle.	Bar from test ingot.	Bar from angle.	Loss of strength in angle.	Bar from test ingot.	Bar from angle.
$\frac{5}{16}$ and $\frac{3}{8}$	39	42270	41300	970	60200	60190	10	70.23	68.62
$\frac{7}{16}$ and $\frac{1}{2}$	46	43070	40170	2900	61360	60660	700	70.19	66.22
$\frac{9}{16}$ and $\frac{5}{8}$	37	42990	39710	3280	62930	61520	1410	68.31	64.55

SEC. 117.—*Physical properties of Pennsylvania Steel Company steels of various compositions, when rolled into angles of different thicknesses.*—The subject is more fully investigated in Table 69, which gives the average results from angle bars of several different kinds of steel. The accidental variations in the metals make it impossible to compare the influence of the thickness upon the ultimate strength, but the column showing the elastic ratio proves that a lower elastic limit follows an increase in thickness. The elongation remains the same for all thicknesses. The reduction of area varies somewhat, but in the groups where a large number of tests make the figures of much value there is a decrease in the heavier bars.

The variation in strength of the different thicknesses is due in part to the fact that the thin pieces are finished at a lower temperature. The effect of such working is investigated in Tables 64 and 65, where pieces of the same billets were heated

differently before rolling and were, therefore, finished under unlike conditions. In the bars finished at the lower temperature the elastic limit was raised very considerably, but the ultimate strength and the ductility did not vary much from the hot-rolled bars. This conclusion has nothing to do with the fact so well known to all manufacturers that if a bar or plate is finished so cool that it looks dark in the sunlight it will give a much higher tensile strength; the bars referred to in the table were all finished somewhat hotter than this, and the small variation in temperature seems to have little effect. These conclusions will be corroborated by Table 70, which records certain tests on acid open-hearth steel.

TABLE 69.

Comparative Physical Properties of Various Steels, Made by The Pennsylvania Steel Company, when Rolled into Angles of Different Thicknesses.

No. of group.	Kind of steel.	Limits of phosphorus; per cent.	Limits of ultimate strength in group; lbs. per sq. inch.	Thickness of angle; inches.	Number of heats in average.	Average elastic limit; lbs. per sq. inch.	Average ultimate strength; lbs. per sq. in	Average elastic ratio; per cent.	Average elongation in 8 in.; per cent.	Average reduction of area; per cent.
I	Basic open-hearth.	below .04	47000 to 55000	$\frac{5}{16}$ to $\frac{3}{8}$	32	36284	52533	69.07	32.18	63.7
				$\frac{7}{16}$ to $\frac{1}{2}$	20	34891	53171	65.62	32.33	62.3
				$\frac{9}{16}$ to $\frac{5}{8}$	14	34026	51903	65.56	32.87	63.4
				$\frac{11}{16}$ to $\frac{7}{8}$	7	32356	51923	62.31	33.86	63.0
II	Basic open-hearth.	below .04	55000 to 63000	$\frac{5}{16}$ to $\frac{3}{8}$	64	39692	58865	67.43	30.52	58.8
				$\frac{7}{16}$ to $\frac{1}{2}$	39	37827	58538	64.62	30.06	56.8
				$\frac{9}{16}$ to $\frac{5}{8}$	17	37487	59235	63.28	29.28	52.6
				$\frac{11}{16}$ to $\frac{7}{8}$	10	36035	59125	60.95	30.58	55.3
III	Acid open-hearth.	.05 to .07	56000 to 64000	$\frac{5}{16}$ to $\frac{3}{8}$	212	40891	60845	67.21	29.35	57.4
				$\frac{7}{16}$ to $\frac{1}{2}$	126	39415	60695	64.94	29.23	55.6
				$\frac{9}{16}$ to $\frac{5}{8}$	81	38645	60558	63.81	28.95	53.8
				$\frac{11}{16}$ to $\frac{3}{4}$	121	37478	59906	62.56	29.32	51.3
				$\frac{13}{16}$ to $\frac{7}{8}$	3	37793	61943	61.01	28.58	48.7
IV	Acid open-hearth.	.07 to .10	56000 to 64000	$\frac{5}{16}$ to $\frac{3}{8}$	50	41143	60064	68.50	28.82	58.4
				$\frac{7}{16}$ to $\frac{1}{2}$	50	40170	60583	66.30	29.05	56.3
				$\frac{9}{16}$ to $\frac{5}{8}$	50	39656	61049	64.96	28.98	54.8
				$\frac{11}{16}$ to $\frac{3}{4}$	50	38338	59763	64.15	29.60	55.3
				$\frac{13}{16}$ to $\frac{7}{8}$	50	37969	61129	62.11	28.85	50.8
V	Acid Bessemer.	.07 to .10	56000 to 64000	$\frac{5}{16}$ to $\frac{3}{8}$	150	43417	60659	71.58	28.07	56.6
				$\frac{7}{16}$ to $\frac{1}{2}$	200	42518	59882	71.00	28.63	56.8
				$\frac{9}{16}$ to $\frac{5}{8}$	200	41063	59415	69.11	28.95	55.6
				$\frac{11}{16}$ to $\frac{3}{4}$	200	38867	58267	66.70	28.37	51.6
VI	Acid open-hearth.	.05 to .07	64000 to 72000	$\frac{5}{16}$ to $\frac{3}{8}$	40	43713	65656	66.58	27.90	55.0
				$\frac{7}{16}$ to $\frac{1}{2}$	29	42191	65631	64.28	27.83	53.7
VII	Acid open-hearth.	.07 to .10	64000 to 72000	$\frac{5}{16}$ to $\frac{3}{8}$	25	44486	66365	67.03	27.19	55.4
				$\frac{7}{16}$ to $\frac{1}{2}$	39	42817	65777	65.09	27.49	53.2
VIII	Acid Bessemer.	.07 to .10	64000 to 72000	$\frac{5}{16}$ to $\frac{3}{8}$	53	46422	66277	70.04	26.42	50.4
				$\frac{7}{16}$ to $\frac{1}{2}$	23	45280	65940	68.66	27.30	51.5

Table 70.

Effect of Finishing 2x⅜-inch Flats of Acid Open-Hearth Steel at Different Temperatures.

(A = finished at usual temperature. B = finished at a low red heat.)

Group.	Ult. strength; per sq. in.	Heat No.	Composition; per cent.			Ultimate strength; pounds per square inch.		Elastic limit; pounds per square inch.		Elongation in 8 inches; per cent.		Reduction of area; per cent.	
			C.	P.	Mn.	A.	B.	A.	B.	A.	B.	A.	B.
I.	58000 to 60000 lbs.	10063	.11	.037	.49	57520	59160	39150	41490	30.50	33.25	63.0	60.9
		10058	.12	.037	.55	57810	61270	39250	44860	32.75	31.75	64.8	58.6
		10055	.12	.030	.65	59060	59140	40800	42760	28.00	30.50	57.9	59.3
		Av.	.12	.035	.56	58130	59857	39733	43037	30.42	31.83	61.9	59.6
II.	60000 to 64000 lbs.	10065	.11	.056	.48	60840	63160	41540	44230	29.25	29.00	61.8	56.5
		10064	.11	.062	.48	60900	63500	41500	45890	30.25	30.50	60.6	56.3
		10071	.13	.065	.48	62230	63820	42290	46730	32.00	30.00	58.9	60.2
		10066	.12	.074	.50	62840	63860	42610	44000	29.25	30.75	61.5	57.3
		Av.	.12	.064	.48	61703	63585	41985	45213	30.19	30.06	60.7	57.6
III.	72000 to 80000 lbs.	10041	.23	.047	.77	72780	74500	47010	49090	25.50	28.75	59.5	57.1
		10045	.23	.052	.86	73060	75910	48660	54240	25.75	28.00	57.8	51.0
		10043	.21	.049	.75	73340	75840	48580	49900	24.00	28.25	55.3	54.6
		10061	.25	.062	.68	75300	77280	49400	51600	25.50	28.50	50.7	54.8
		10034	.25	.059	.78	76860	79430	49340	54920	22.50	27.50	54.4	51.2
		10047	.25	.045	.80	77340	80260	49460	54800	23.75	26.75	52.3	52.4
		10068	.26	.062	.79	78280	80880	50860	57220	26.00	27.50	48.6	47.4
		10042	.26	.042	.76	78540	80560	49930	54900	24.25	24.00	53.8	49.3
		Av.	.24	.052	.77	75688	78083	49155	53334	24.66	27.41	54.1	52.2

SEC. 118.—*Comparative physical properties of hand and guide rounds.*—The fact that the elongation is as high on thick as on thin angles is contrary to a prevailing opinion concerning the effect of surface work upon rolled steel. Further information is given in Table 71, which shows the comparative results on hand and guide rounds from the same heats.

Table 71.

Comparative Physical Properties of Hand Rounds and Guide Rounds from the Same Acid Open-Hearth Heats.

Group.	Limits of ult. strength in group; pounds per sq. inch	Number of heats in group.	Average manganese; per cent.	Ultimate strength; lbs. per sq. inch.		Elastic limit; lbs. per square inch.		Elongation in 8 inches; per cent.		Reduction of area; per cent.	
				Hand.	Guide.	Hand.	Guide.	Hand.	Guide.	Hand.	Guide.
I	56000 to 64000	3	.41	59830	59192	42548	38848	28.23	29.35	55.90	61.85
II	70000 to 75000	5	.76	72464	69750	48024	45601	22.77	24.73	40.77	48.98
III	75000 to 80000	5	.81	78805	77790	51943	51983	23.55	24.92	46.09	53.30
IV	80000 to 86000	6	.79	83813	82524	52986	52863	22.74	24.51	45.69	55.57
Av. of all heats,		19	.73	75722	74232	49758	48495	23.83	25.44	46.11	54.23

A guide round is made in one pass from an ellipse, while a hand round is put through the same pass several times, being turned one-quarter way each time in order to obtain a true circular section. This has the effect of finishing the bar somewhat cooler than a guide round, and thus naturally gives a higher ultimate strength, while it also works the skin of the piece during the finishing process without any great reduction in diameter. It will be seen that nothing is gained by this operation, for, although the guide rounds are slightly reduced in strength, they are considerably better in elongation and reduction of area.

TABLE 72.

Changes in the Physical Properties of Steel by Variations in the Details of Plate-Rolling; Classified According to Strength of Preliminary Test.

	Limits of ult. strength of preliminary test; lbs. per square inch.	Thickness of plate; in inches.	Number of heats tested.	Increase in ultimate strength from preliminary test to plate; pounds per square inch.	Ultimate strength; lbs. per sq. in.			Elastic limit of plate; lbs. per square inch.	Elastic ratio of plate; per cent.	Elongation of plate in 8 inches; per cent.	Reduction of area of plate; per cent.
					Finished plate.	Preliminary test bar.	Average increase from preliminary test to plate.				
Basic open-hearth steel.	44000 to 52000	5/16	12	more than 7500	60040	49479	10561	44659	74.4	25.94	52.9
			18	less than 7500	56475	51177	5298	42570	75.4	26.31	52.3
		3/8	13	more than 5500	57807	50020	7787	40407	69.9	26.94	57.4
			19	less than 5500	54799	51033	3766	39675	72.4	28.78	61.1
	52000 to 58000	5/16	94	more than 4000	59582	54096	5486	44653	74.9	26.44	59.6
			68	less than 4000	58323	55741	2582	43028	73.8	27.10	55.3
		3/8	69	more than 3000	58705	54013	4692	40420	68.9	28.50	56.9
			60	less than 3000	57021	55328	1693	40266	70.6	28.37	57.8
		7/16	10	more than 3000	59414	53557	5857	38222	64.3	28.09	59.9
			16	less than 3000	56501	54786	1715	36525	64.6	30.58	58.5
		1/2	7	more than 3000	59135	53934	5201	38078	64.4	27.90	57.9
			10	less than 3000	56977	55840	1137	36770	64.5	27.13	52.5
Acid open-hearth steel.	58000 to 64000	3/8	8	more than 2000	62228	59506	2722	42687	68.6	25.69	51.0
			4	less than 2000	61425	60550	875	42325	68.9	25.41	51.0
		7/16	11	more than 1000	61827	59706	2121	42027	68.0	25.12	53.2
			9	less than 1000	59022	59320	....	39875	67.6	24.46	55.5
		1/2	19	more than 1000	61174	59573	1601	40157	65.7	24.19	50.2
			14	less than 1000	60293	60408	....	39693	65.8	24.69	48.7

SEC. 119.—*Changes in the physical properties of steel by variations in the details of plate-rolling.*—It has been already stated that it is the practice at The Pennsylvania Steel Works to roll a preliminary test-bar from each open-hearth heat for

physical testing, and that the ultimate strength of this bar corresponds closely with that of angles rolled from the same charge. In the case of plates, on the contrary, there is often a considerable variation, and Table 72 investigates the effect of such differences upon the physical qualities.

TABLE 73.

Changes in the Physical Properties of Steel by Variations in the Details of Plate-Rolling; Classified According to Strength of Finished Plate.

	Limits of ult. strength of finished plate; pounds per square inch.	Thickness of plate in inches.	Number of heats tested.	Increase in ultimate strength from preliminary test to plate; pounds per square inch.	Ultimate strength; pounds per square inch.			Elastic limit of plate; pounds per square inch.	Elastic ratio of plate; per cent.	Elongation of plate in 8 inches; per cent.	Reduction of area of plate; per cent.
					Finished plate.	Preliminary test bar.	Av. increase from preliminary test to plate.				
Basic open-hearth steel.	50000 to 58000	$\frac{5}{16}$	35	more than 4000	56971	51963	5008	43106	75.6	26.66	57.8
			30	less than 4000	56652	54680	1972	41345	73.0	27.35	55.2
		$\frac{3}{8}$	42	more than 3000	56370	52161	4209	40387	71.6	28.28	58.5
			49	less than 3000	55958	54441	1517	39759	71.0	28.66	58.2
		$\frac{7}{16}$	7	more than 1700	55963	53391	2572	37613	67.2	30.27	58.6
			6	less than 1700	53981	53213	768	34802	64.5	31.43	59.6
		$\frac{1}{2}$	3	more than 1100	56633	54076	2557	36366	64.2	27.91	54.7
			4	less than 1100	55292	54843	449	36150	65.4	28.50	53.7
	58000 to 64000	$\frac{5}{16}$	39	more than 4000	60130	51234	5896	44572	74.1	26.63	58.7
			38	less than 4000	59344	56401	2943	44054	74.2	26.92	56.2
		$\frac{3}{8}$	15	more than 3000	59750	53676	6074	40928	68.5	27.87	57.6
			15	less than 3000	58920	56969	1951	40855	69.3	28.07	58.7
Acid open-hearth steel.	56000 to 64000	$\frac{3}{8}$	6	more than 2550	62841	59151	3690	43933	69.9	25.92	50.5
			6	less than 2550	61080	60557	523	41200	67.4	25.04	52.0
		$\frac{7}{16}$	9	more than 1400	61833	59647	2186	42512	68.7	25.28	54.9
			11	less than 1400	59527	59439	88	40230	67.6	24.45	53.8
		$\frac{1}{2}$	17	more than 1700	61241	59442	1799	40110	65.5	24.38	50.7
			16	less than 1700	60331	60442	....	39800	66.0	24.43	48.6

It is assumed that the preliminary test-piece is the standard, and whatever difference from this is shown in the plate is due to the conditions of rolling. On this basis it is possible to compare those plates which show a great with those which show a less variation from the standard, and note the corresponding ductility. In the first division, for example, it was found that the average increase in strength from the preliminary bar to the finished plate was 7500 pounds per square inch. Consequently this figure was taken as a dividing line, and a

comparison was made of the heats showing more than this difference with those showing less. The same rule was followed in all the other divisions.

Table 73 gives a different view of the same data, the groups being divided on the less logical but more practical basis of the strength of the finished plate. It will be seen that the elongation for a given tensile strength is not seriously affected by the variations in rolling, but that the hotter finished plates are somewhat better. The elastic ratio exhibits much less variation than would be expected, and this might throw some doubt on the results, but all the different groups teach the same lesson, and in some of them the number of heats is so large as to give great weight to the conclusion. The plates were all rolled from slabs, which in turn had been rolled from large ingots, so that there was ample work on all thicknesses.

TABLE 74.

Comparative Physical Properties of Angles and Sheared Plates, Both Being Made from Pennsylvania Steel Company Steel.

	Thickness of bar; in inches.	Kind of piece.	No. of heats in average.	Ult. strength; pounds per square inch.	Elastic limit; pounds per square inch.	Elastic ratio; per cent.	Elongation in 8 inches; per cent.	Reduction of area; per ct.
Basic open-hearth soft steel, below .04 per cent. in phosphorus.	$\frac{5}{16}$ to $\frac{3}{8}$	Angles	32	52533	36284	69.07	32.18	63.7
		Plates	107	54998	38017	69.12	29.28	58.6
	$\frac{7}{16}$ to $\frac{1}{2}$	Angles	20	53171	34891	65.62	32.33	62.3
		Plates	102	55017	34947	63.52	29.03	61.5
Basic open-hearth medium steel, below .04 per cent. in phosphorus.	$\frac{5}{16}$ to $\frac{3}{8}$	Angles	64	58865	39692	67.43	30.52	58.8
		Plates	265	58271	40349	69.24	28.27	58.1
Acid open-hearth soft steel, below .08 per cent. in phosphorus.	$\frac{5}{16}$ to $\frac{3}{8}$	Angles	212	60845	40891	67.21	29.35	57.4
		Plates	190	60217	43278	71.87	25.98	57.4
	$\frac{7}{16}$ to $\frac{1}{2}$	Angles	126	60695	39415	64.94	29.23	55.6
		Plates	59	60768	39061	64.28	25.87	55.1
	$\frac{9}{16}$ to $\frac{5}{8}$	Angles	81	60558	38645	63.81	28.95	53.8
		Plates	13	60666	37932	62.53	24.67	52.7

SEC. 120.—*Comparative physical properties of plates and angles.*—It is very difficult to make a comparison of two different structural shapes, since it does not often happen that the same heat is rolled into more than one kind of section, but an attempt is made to do this in Table 74. The prime requisite is that the steel in both cases shall be of the

same manufacture, and this specification is satisfied in the present instance. The figures for the angles are found by combining certain groups in Table 69, which was compiled from the records of The Pennsylvania Steel Company, while the plates represent the average obtained from The Paxton Rolling Mills, which was running on slabs from the same works.

The one predominant feature is the lower elongation in the plates. This may be explained by the fact that the metal receives a less thorough compression in the plate train than it does in the rolling of angles, in which latter case it undergoes a certain amount of lateral thrust.

SEC. 121.—*Effect of thickness on the physical properties of plates.*—The effects caused by variations in rolling temperature appear in their most marked degree in the comparison of plates of different gauges. It is not customary to test the same heat in several sizes, but by long experience the manufacturer is able to judge the relative properties of each thickness. The heads of two widely-known plate mills have given me as their estimate that, taking one-half inch as a basis, there will be the following changes in the physical properties for every increase of one-quarter inch in thickness:

(1) A decrease in ultimate strength of 1000 pounds per square inch.

(2) A decrease in elongation of one per cent. when measured in an 8-inch parallel section.

(3) A decrease in reduction of area of two per cent.

W. R. Webster* gives the same data on ultimate strength, but does not mention the relation of section to elongation.

It is, therefore, plain that in the writing of specifications some allowance must be made for these conditions, since a requirement which is perfectly proper for a three-eighth-inch plate will be unreasonable for a 1½-inch. Moreover, the effect is cumulative, since a harder steel must be used in making the thick plate and this will tend to lessen the ductility rather than make up for the reduction caused by the larger section. In plates below three-eighth inch in

* *Observations on the Relations between the Chemical Constitution and Ultimate Strength of Steel. Journal I. and S. I.*, Vol. I, 1894, p. 329.

thickness it is also necessary to make allowances, since it is almost impossible to finish them at a high temperature, and the test will give a high ultimate strength and a low ductility.

These conditions have now been officially recognized by the United States Government, for the rules of the Board of Supervising Inspectors, issued February 19, 1896, contain the following clause:

"The sample must show, when tested, an elongation of at least 25 per cent. in a length of two inches for thicknesses up to one-quarter inch, inclusive; and in a length of four inches, for over one-quarter to seven-sixteenths, inclusive; and in a length of eight inches, for over seven-sixteenths to one-inch, inclusive; and in a length of six inches, for all thicknesses over one-inch."

It is to be hoped that constructive engineers will follow this example in recognizing the influence of causes over which the manufacturer has no control.

CHAPTER XV.

ANNEALING.

SECTION 122.—*Effect of annealing on the physical properties of rolled bars.*—It is a well-known fact that annealing tends to remove the strains which are created by cold rolling and distortion, but it is not generally understood how profound are the changes produced. Table 75 will show the results obtained on rounds and flats by comparing the natural bar with the annealed specimen when all the pieces were rolled from billets of the same size and on the same mill. The reheating was done in a muffle heated by a soft-coal fire, the bar being withdrawn when it had reached a dull yellow heat. This is the practice which was followed in other experiments related in this chapter.

The decrease in ultimate strength by annealing the Bessemer bars averaged 4175 pounds per square inch in the rounds and 5683 pounds in the flats, while the open-hearth was lowered 5134 pounds in the rounds and 7649 in the flats. In this important and fundamental quality the two kinds of steel are very similarly affected, but in other particulars there seems to be a radical difference which is difficult to explain.

The elongation of the Bessemer steel is increased by annealing in every case except two, the average being 1.33 per cent., while the open-hearth metal shows a loss in three cases, with an average loss for all cases of 0.21 per cent. This is not very conclusive, but there is a more marked difference in the reduction of area, for in the Bessemer steel there is an increase in the annealed bar in every case varying from 7 to 15.18 per cent., while the open-hearth showed an increase in only three cases, the maximum being 2.81 per cent., and a decrease in five cases, the greatest loss being 7.20 per cent.

TABLE 75.

Effect of Annealing on Rounds and Flats of Bessemer and Acid Open-Hearth Steel.

A 4″x4″ billet from each heat was rolled into a 2″x⅜″ flat and another into a ¾″ round.

	Limits of ultimate strength; pounds per square inch.	Kind of steel.	Number of heats in average.	Condition of bar.	Ultimate strength; pounds per square inch.	Elastic limit; pounds per square inch.	Elongation in 8 inches; per cent.	Reduction of area; per cent.	Elastic ratio; per cent.
¾-inch rounds.	56000 to 60000	Bess.	11	Natural	58869	42318	27.75	58.83	71.88
				Annealed	55703	37828	29.14	66.55	67.91
		O. H.	4	Natural	58568	40300	29.69	60.78	68.81
				Annealed	54098	31823	28.75	62.65	58.82
	60000 to 64000	Bess.	6	Natural	62087	45323	27.04	55.31	73.00
				Annealed	59372	40570	30.13	65.50	68.33
		O. H.	7	Natural	62187	42606	28.04	62.16	68.51
				Annealed	58364	35120	28.61	63.47	60.17
	64000 to 68000	Bess.	9	Natural	66241	47568	26.08	50.07	71.81
				Annealed	61694	42228	28.25	62.91	68.45
	68000 to 72000	Bess.	3	Natural	70457	50263	24.75	48.30	71.34
				Annealed	65903	44660	26.08	63.23	67.76
		O. H.	2	Natural	70530	49000	26.88	61.10	69.47
				Annealed	65500	37685	23.38	55.30	57.53
	72000 to 80000	Bess.	4	Natural	77440	53760	24.06	42.35	69.42
				Annealed	71548	47643	25.81	57.53	66.59
		O. H.	12	Natural	76616	51108	24.52	53.73	66.71
				Annealed	69402	40505	23.04	56.54	58.36
2x⅜-inch flats.	56000 to 60000	Bess.	11	Natural	58458	41698	31.45	56.13	71.33
				Annealed	54194	35603	30.05	63.13	65.70
		O. H.	4	Natural	58130	40400	30.13	61.75	69.51
				Annealed	51418	30393	31.06	60.50	59.11
	60000 to 64000	Bess.	6	Natural	60825	43135	30.42	56.20	70.92
				Annealed	56192	37542	30.63	63.38	66.81
		O. H.	7	Natural	62089	42441	30.14	60.86	68.36
				Annealed	55021	31576	30.36	60.00	57.39
	64000 to 68000	Bess.	9	Natural	64621	45194	28.42	47.80	69.94
				Annealed	58838	38476	28.36	59.01	65.39
	68000 to 72000	Bess.	3	Natural	69773	49060	26.67	48.40	70.31
				Annealed	64160	43770	28.58	59.50	68.22
		O. H.	2	Natural	69420	45090	25.63	59.30	64.96
				Annealed	60850	34000	26.50	52.10	55.87
	72000 to 80000	Bess.	4	Natural	76900	52240	23.44	40.15	67.93
				Annealed	68780	43568	26.38	51.00	63.34
		O. H.	12	Natural	75865	49691	24.69	54.40	65.50
				Annealed	67618	39403	26.31	51.36	58.27

The elastic limit fell much more than the ultimate strength, and here again the Bessemer seems to be different from the

open-hearth steel, for while the elastic ratio of the former is lowered from 2.1 to 4.7 per cent. by annealing, the latter loses from 7.2 to 11.9 per cent.

SEC. 123.—*Comparative physical properties of annealed bars, and natural bars of similar tensile strength.*—It will not do to draw a general conclusion from these limited data on the nature of the two kinds of steel, but whether further experiment would or would not corroborate these results, it is quite certain that annealing may produce grave differences in physical properties in steels of similar composition which have been rolled in the same manner and treated at the same time, even when the effect upon the ultimate strength has been the same.

TABLE 76.

Comparison of the Natural and Annealed Bessemer Steel Bars given in Table 75, which Show About the Same Ultimate Strength.

	Group.	Limits of ultimate strength in group; pounds per square inch.	No. of heats in average.	Condition of bar.	Ultimate strength; pounds per square inch.	Elastic limit; pounds per square inch.	Elongation in 8 inches; per cent.	Reduction of area; per cent.	Elastic ratio; per cent.
¾-inch rounds.	I	56000 to 60000	11	Natural	58869	42318	27.75	58.83	71.88
			17	Annealed	56998	38796	29.49	66.18	68.06
	II	60000 to 64000	6	Natural	62087	45323	27.04	55.31	73.00
			9	Annealed	61694	42228	28.25	62.91	68.45
	III	64000 to 68000	9	Natural	66241	47568	26.08	50.07	71.81
			3	Annealed	65903	44660	26.08	63.23	67.76
	IV	68000 to 72000	3	Natural	70457	50263	24.75	48.30	71.34
			4	Annealed	71548	47643	25.81	57.53	66.59
2x⅜-in. flats.	V	56000 to 60000	11	Natural	58458	41698	31.45	56.13	71.33
			15	Annealed	57780	38102	29.27	60.76	65.95
	VI	64000 to 68000	9	Natural	64621	45194	28.42	47.80	69.94
			3	Annealed	64160	43770	28.58	59.50	68.22
	VII	68000 to 72000	3	Natural	69773	49060	26.67	48.40	70.31
			4	Annealed	68780	43568	26.38	51.00	63.34

It is also certain that even in the Bessemer steel the marked increase in ductility is purchased at a great sacrifice of strength, and it is an open question whether the gain is not more than balanced by the loss, and whether an equal degree of toughness could not be secured by using a softer steel in

its unannealed state. A comparison of the natural and annealed bars of corresponding tensile strength in Table 75 will give the results shown in Tables 76 and 77.

TABLE 77.

Comparison of the Natural and Annealed Open-Hearth Steel Bars Given in Table 75, which Show About the Same Ultimate Strength.

	Group.	Limits of ultimate strength in group; pounds per square inch.	Number of heats in average.	Condition of bar.	Ultimate strength; pounds per square inch.	Elastic limit; pounds per square inch.	Elongation in 8 inches; per cent.	Reduction of area; per cent.	Elastic ratio; per cent.
¾-inch rounds.	I	56000 to 60000	4 7	Natural Annealed	58568 58364	40300 35120	29.69 28.61	60.78 63.47	68.81 60.17
	II	68000 to 72000	2 12	Natural Annealed	70530 69402	49000 40505	26.88 23.04	61.10 56.54	69.47 58.36
2x⅜-inch flats.	III	55000 to 60000	4 7	Natural Annealed	58130 55021	40400 31576	30.13 30.36	61.75 60.00	69.51 57.39
	IV	60000 to 64000	7 2	Natural Annealed	62089 60850	42441 34000	30.14 26.50	60.86 52.10	68.36 55.87
	V	66000 to 70000	2 12	Natural Annealed	69420 67618	45090 39403	25.63 26.31	59.30 51.36	64.96 58.27

SEC. 124.—*Effect of annealing on bars rolled at different temperatures.*—These results show that the annealed bar has a very much lower elastic limit than a natural bar of the same ultimate strength, and oftentimes has less ductility. The difference between the Bessemer and open-hearth steels can not be due to irregular finishing, since all the bars were rolled at the same time, and further experiments given in Table 78 indicate that the same law holds good whether the metal is finished hot or cold.

In the bars which are finished at the usual temperature there is a loss in strength due to annealing of from 6000 to 9000 pounds per square inch, and a lowering in the elastic limit of from 8000 to 11000 pounds. In the colder finished bars the loss in strength is from 8000 to 11000 pounds and the elastic limit is lowered from 8000 to 13000 pounds. Thus in both cases the elastic limit is affected much more than the

ultimate strength, and the result is seen in a lower elastic ratio. The ductility does not seem to be materially improved in any instance.

The cold finishing raised the strength of the bars 1727 pounds per square inch in Group I, 1882 pounds in Group II, and 2395 pounds in Group III. Annealing lowered the strength of these cold-finished bars so that in Group I it was 766 pounds per square inch below the annealed hot-finished bar, while in Group II it was 595 pounds above it, and in Group III 474 pounds. The effect upon the elastic limit is not as thorough, and the influence of the cold finishing may be seen in the higher elastic ratio of the annealed cold-finished bar.

TABLE 78.

Effect of Annealing Acid Open-Hearth Rolled Steel Bars 2x$\frac{5}{8}$ inches.

Group.	No. of heats in group.	Limits of tensile strength; pounds per square in. and composition; per cent.	Temperature at which bars were finished.	Condition of bar.	Ultimate strength; pounds per square inch.	Elastic limit; pounds per square inch.	Elongation in 8 inches; per cent.	Reduction of area; per cent.	Elastic ratio; per cent.
I	3	56000 to 60000 C, .12; P, .035; Mn, .56.	Usual	Nat. Ann.	58130 52323	39733 31677	30.42 30.75	61.90 60.63	68.4 60.5
			Dull red	Nat. Ann.	59857 51557	43037 33893	31.83 32.92	59.60 63.60	71.9 65.7
II	4	60000 to 64000 C, .12; P, .086; Mn, .48.	Usual	Nat. Ann.	61703 54463	41985 30953	30.19 30.38	60.70 59.35	68.0 56.8
			Dull red	Nat. Ann.	63585 55058	45213 36988	30.06 30.94	57.58 61.53	71.1 67.2
III	8	72000 to 80000 C, .24; P, .052; Mn, .77.	Usual	Nat. Ann.	75688 66584	49155 37934	24.66 26.06	54.05 50.74	64.9 57.0
			Dull red	Nat. Ann.	78083 67058	53334 40343	27.41 26.50	52.23 53.41	68.3 60.2

SEC. 125.—*Effect of annealing on bars rolled under different conditions of work and temperature.*—All these results will be corroborated by Tables 79 and 80, which show the effect of annealing on bars which have been finished under different conditions. In Table 79, where each bar was made from a billet of proportionate size, the pieces would be in the rolls about the same length of time, so that the only difference in

character will be due to the more rapid loss in heat from a thin bar and from the more thorough compression. In Table 80, where all bars were rolled from the same-sized billet, these factors are supplemented by the extra cooling during the longer exposure in the rolls.

TABLE 79.

Effect of Annealing on Bars of Different Thickness, when the Percentage of Reduction in Rolling had been Constant for All Pieces.

Heat number.	Size of billet in inches.	Size of bar in inches.	Ultimate strength; lbs. per sq. inch.		Elastic limit; lbs. per sq. inch.		Elongation in 8 inches; per cent.		Reduction of area; per cent.	
			Natural.	Annealed.	Natural.	Annealed.	Natural.	Annealed.	Natural.	Annealed.
4605	4x4	2x5/8	51640	45870	33440	25680	37.50	37.50	60.1	64.8
	3 5/8x3 5/8	2x1/2	51120	45100	32650	26350	32.50	38.00	56.4	64.0
	3x3	2x3/8	50850	46350	35700	25980	32.50	39.50	60.8	67.0
	2 1/2x2 1/2	2x1/4	53320	46010	37360	26680	31.25	34.00	61.0	64.3
	2x1 5/8	2x1/8	....	44960	....	28570	....	31.25	....	67.2
9227	4x4	2x5/8	59540	53360	37050	29030	35.00	32.50	60.0	59.7
	3 5/8x3 5/8	2x1/2	59730	51360	38100	28410	29.75	32.75	56.4	60.1
	3x3	2x3/8	60950	52460	42110	29860	30.00	31.75	60.0	56.6
	2 1/2x2 1/2	2x1/4	62350	51230	43070	28580	27.50	30.00	60.7	62.4
	2x1 5/8	2x1/8	65130	54110	52180	31170	26.25	28.25	58.9	64.9
1509	4x4	2x5/8	67860	63560	42850	38750	25.00	26.50	40.8	57.3
	3 5/8x3 5/8	2x1/2	67550	62680	43190	38810	26.25	29.00	46.1	58.4
	3x3	2x3/8	67470	62660	44090	40430	26.25	29.25	53.2	56.1
1440	4x4	2x5/8	72840	68940	47080	43580	25.00	27.00	40.7	53.6
	3 5/8x3 5/8	2x1/2	71230	67060	46010	42020	26.25	29.00	40.5	53.4
	3x3	2x3/8	72950	67860	48760	43920	26.25	26.25	52.1	55.4
	2 1/2x2 1/2	2x1/4	73620	69720	51550	48380	26.25	26.50	45.9	54.1
	2x1 5/8	2x1/8	78560	74000	58140	53200	22.75	25.25	52.0	53.6

SEC. 126.—*Effect of annealing on plates of the same charge which showed different physical properties.*—This matter of finishing temperature is of supreme importance in filling specifications on structural material, more especially in the rolling of thin plates, for it will often happen that different members of one heat will show wide variations in tensile strength when the metal itself is practically homogeneous. Table 81 will illustrate this point by giving the records of test-pieces which gave the greatest variations in any one heat, and comparing the natural bar with a piece of the same strip when annealed.

It will be seen that annealing has almost wiped away the variations in each heat, and it is therefore quite certain that the differences lie in the rolling history. The true way of testing the homogeneity of steel, or of comparing two different samples, is to make the tests on annealed bars. This practice was pursued in Chapter XIII.

TABLE 80.

Effect of Annealing on Bars of Different Thickness, when All Pieces had been Rolled from Billets 3 Inches Square.

Heat number.	Size of bar in inches.	Ult. strength; lbs. per sq. inch.		Elastic limit; lbs. per sq. inch.		Elongation in 8 in.; per cent.		Reduction of area; per ct.	
		Nutural.	Annealed.	Natural.	Annealed.	Natural.	Annealed.	Natural.	Annealed.
	2x5/8	51370	45490	32860	25560	34.50	36.75	59.6	65.6
	2x1/2	51070	43280	33200	24110	31.50	38.00	59.2	64.2
4605	2x3/8	50850	46350	35700	25980	32.50	39.50	60.8	67.0
	2x1/4	52960	44470	36220	.....	31.25	38.50	63.2	69.6
	2x1/8	55560	45830	47380	27780	30.00	33.25	53.2	69.0
	2x5/8	59690	52880	37000	29030	35.00	32.00	55.4	56.4
	2x1/2	60350	52270	38560	28460	29.50	32.00	58.8	55.1
9227	2x3/8	60950	52460	42110	29860	30.00	31.75	60.0	56.6
	2x1/4	62230	53500	42600	31000	25.75	30.75	55.9	58.4
	2x1/8	66340	54310	49860	30600	27.50	26.25	56.6	61.6
	2x5/8	65600	61480	40980	37840	29.50	29.00	50.9	57.1
	2x1/2	67310	64500	43090	41400	26.25	29.25	47.1	56.0
1509	2x3/8	67470	62660	44090	40430	26.25	29.25	53.2	56.1
	2x1/4	69210	65240	47950	44510	26.50	30.50	54.1	52.6
	2x1/8	72100	66940	54060	49000	27.75	27.50	55.0	52.6
	2x5/8	72440	69730	46440	45250	27.50	24.25	45.7	56.3
	2x1/2	72570	67980	46200	42000	27.25	28.25	47.3	54.2
1440	2x3/8	72950	67860	48760	43920	26.25	26.25	52.1	55.4
	2x1/4	75620	71560	51160	48250	25.00	26.50	53.5	59.0
	2x1/8	77500	70820	60920	56420	26.00	25.50	46.8	59.9

SEC. 127.—*Effect of annealing on the physical properties of eye-bar flats.*—It does not follow that plates and bars should be annealed to put them into their best condition. On the contrary, the foregoing tests have shown that very little is gained in ductility, while there is quite a loss in working strength, and that it would be better and much cheaper to choose a softer steel in its natural state. Moreover, it must be considered that the bars which have been discussed in the foregoing tables have been small test-pieces which could be treated under fairly constant conditions, and even then the results are far from regular.

Table 81.

Showing that Rolled Plates of the Same Acid Open-Hearth Heat, which show Wide Variations in their Physical Properties, are Made Alike by Annealing.

Note.—In each case, *A* is the test giving the highest tensile strength of any plate in the heat, and *B* is the one giving the lowest. Carbon was determined by color and is therefore not reliable.

Heat number.	Thickness of plates.	Condition of test bar.	Test mark.	Ultimate strength; pounds per square inch.	Elastic limit; pounds per square inch.	Elongation in 8 inches; per cent.	Reduction of area; per cent.	Elastic ratio; per cent.	Chemical composition; per cent.			
									C.	P.	Mn.	S.
5633	$\frac{1}{4}$	Natural	A	61000	53200	21.50	61.9	87.2	.16	.015	.32	.022
		Natural	B	56480	46300	25.25	60.0	82.0	.12	.015	.31	.019
		Annealed	A	47750	29980	34.50	67.0	62.8	...	...	...	...
		Annealed	B	46970	30690	35.00	64.5	65.3	...	...	...	...
5658	$\frac{1}{4}$	Natural	A	65370	52560	21.75	58.7	80.4	.14	.009	.45	.025
		Natural	B	60380	48800	21.50	61.1	80.8	.10	.012	.45	.020
		Annealed	A	52160	32450	32.00	57.0	62.2	...	...	...	...
		Annealed	B	50260	33340	32.50	62.6	66.3	...	...	...	...
8217	$\frac{1}{4}$	Natural	A	64620	53140	25.00	58.1	82.2	.16	.021	.44	.031
		Natural	B	59960	48490	21.50	45.5	80.9	.14	.016	.44	.025
		Annealed	A	52820	35450	27.00	62.2	67.1	...	...	...	...
		Annealed	B	50000	31840	31.50	56.4	63.7	...	...	...	...
8226	$\frac{1}{4}$	Natural	A	64260	54370	21.00	50.6	84.6	.12	.036	.34	.058
		Natural	B	57040	39990	28.75	56.6	70.1	.12	.034	.32	.047
		Annealed	A	54070	38520	27.50	64.4	71.2	...	...	...	...
		Annealed	B	53960	38520	29.50	63.3	71.4	...	...	...	...
8231	$\frac{5}{16}$	Natural	A	64480	50560	26.00	58.8	78.4	.13	.021	.55	.048
		Natural	B	61100	45030	26.00	48.0	73.7	.11	.018	.51	.044
		Annealed	A	53830	34870	31.25	61.9	64.8	...	...	...	..
		Annealed	B	52180	33780	34.25	63.2	64.7	...	...	...	...
8233	$\frac{1}{4}$	Natural	A	66360	59100	20.75	52.7	89.1	.11	.026	.37	.033
		Natural	B	58160	47630	24.50	60.3	81.9	.11	.020	.39	.028
		Annealed	A	52760	36940	33.00	65.0	70.0	...	...	...	...
		Annealed	B	51480	40480	28.75	56.0	78.6	...	...	...	...
8234	$\frac{5}{16}$	Natural	A	66300	49440	20.75	57.5	74.6	.15	.024	.49	.022
		Natural	B	61360	47930	27.00	61.7	78.1	.14	.021	.47	.023
		Annealed	A	55560	37360	28.25	60.0	67.2	...	...	...	...
		Annealed	B	54033	34443	31.75	63.7	63.7	...	...	...	...
8235	$\frac{1}{4}$	Natural	A	63220	58300	13.50	54.9	92.2	.10	.017	.33	.035
		Natural	B	58240	47630	21.25	53.5	81.8	.11	.017	.35	.034
		Annealed	A	47740	29930	33.25	63.9	62.7	...	...	...	...
		Annealed	B	47600	30530	34.00	57.2	64.1	..	...	...	...
8236	$\frac{5}{16}$	Natural	A	64020	49510	23.25	58.1	77.3	.11	.025	.46	.037
		Natural	B	58720	42960	30.25	60.0	73.2	.13	.017	.45	.022
		Annealed	A	53860	33710	29.25	58.6	62.6	...	...	...	...
		Annealed	B	50660	32710	35.00	64.7	64.6	...	...	...	...

These deductions will be corroborated by Table 82, which gives the parallel records of pieces cut from a flat bar in its natural state, and the full-sized eye-bars after annealing. The steel was made and rolled by one of our largest Ameri-

can works. It is plain that there is a great gain in the elongation, but the reduction of area is unaffected and there is a decided loss in elastic and ultimate strength.

SEC. 128.—*Methods of annealing.*—A different view of the subject is taken by Gus. C. Henning.* He states that steel is injured by annealing if it is in contact with flame, while it is improved if it is reheated in a sealed muffle. I cannot assent to this broad conclusion, for, while it may be true that a flame can be run too hot and the piece be burned through carelessness, it by no means follows that such local overheating is necessary; nor is there any ground for assuming the absorption of deleterious gases from a proper flame. Moreover, the figures which he gives do not show a decided improvement of any kind in the bars which were heated in a retort.

TABLE 82.

Comparative Tests of Eye-Bar Steel.

Heat number.	Longitudinal strip; cut from near the edge of eye-bar; natural.					Full-sized eye-bar; annealed.				
	Elastic limit; pounds per square in.	Ultimate strength; pounds per square in.	Elongation in 8 inches; per cent.	Reduction of area; per cent.	Elastic ratio; per cent.	Elastic limit; pounds per square in.	Ultimate strength; pounds per square in.	Elongation in 8 inches; per cent.	Reduction of area; per cent.	Elastic ratio; per cent.
1	40710	68830	27.00	47.18	59.1	36500	62100	43.70	32.60	58.8
2	41570	71400	26.25	50.08	58.2	40400	65200	40.00	46.55	62.0
3	39780	69460	25.75	44.31	57.3	38300	63250	41.85	45.95	60.5
4	40880	69400	25.00	48.41	58.9	40600	67100	36.00	45.00	60.5
5	41480	72320	24.50	46.78	57.4	42100	65000	36.60	48.40	64.8
6	41310	73640	23.75	36.54	56.1	33700	57600	45.60	50.00	58.5
7	40370	72060	25.60	40.00	56.0	35400	64700	45.62	61.30	54.7
8	41900	76700	25.75	43.76	54.6	39600	67700	38.43	42.65	58.5
9	41070	69680	27.00	44.33	58.9	35900	65200	40.00	46.40	55.1
Av.	41008	71499	25.62	44.60	57.4	38056	64206	40 87	46.54	59.3

It is stated (*loc. cit.*, p. 577) that most of the "flats" were "properly" annealed, and so I have averaged the records which he gives of the natural and the reheated pieces, separating them into three groups according to thickness. The results are given in Table 83. It will be seen that the metal has undergone very little change at all, and it is impossible to see anything which can be called a radical improvement.

Any attempt to carry out a general system of annealing

* *Trans. Am. Soc. Mech. Eng.*, Vol. XIII, p. 572.

plates and shapes will result in wide variations in temperatures and rates of cooling, for it will be impossible to have a large pile of metal heated uniformly throughout, since the outside of the lot will be at a full heat when the interior is unaffected. Since the manufacturer may always manipulate the operation so as to affect the test-pieces in preference to the rest of the steel, and since it will be to his interest to keep the temperature as low as possible to avoid warping, there will be no certainty either that the work has been properly carried out or that it has been of the least advantage.

TABLE 83.

Comparative Physical Properties of Natural and Annealed Flat Steel Bars; as given by Henning.*

Number of pieces.	Thickness of flats; in inches.	Average thickness of flats; in inches.	Condition of bar.	Elastic limit; pounds per square inch.	Ult. strength; pounds per square inch.	Elongation in 8 inches; per cent.	Reduction of area; per cent.	Elastic ratio; per cent.
10	$\frac{7}{8}$ to $1\frac{5}{16}$	1.12	Natural Annealed	38737 40299	71226 69296	23.89 25.53	47.0 53.5	54.4 58.2
16	$1\frac{3}{8}$ to $1\frac{7}{16}$	1.41	Natural Annealed	35411 38298	68465 67971	24.38 24.95	46.65 49.17	51.7 56.3
12	$1\frac{1}{2}$ to $1\frac{7}{8}$	1.62	Natural Annealed	35729 38692	69490 69411	24.25 25.28	47.27 49.85	51.4 55.7

Annealing is useful in removing the strains caused by distortion, for in such cases the gain in safety more than counterbalances the risk of loss of strength, but it may be accepted as a general rule that steel is in its best condition when it leaves the rolling mill; that the shop treatment should retain, as far as possible, the natural qualities of the metal; and that the bar should be heated only when it is necessary to make a permanent bend.

* *Trans. Amer. Soc. Mech. Eng.*, Vol. XIII, p. 586, *et seq.* The factor which Mr. Henning calls the "yield point" is here called the elastic limit. I have omitted from the averages the tests which are noted in the original as being wrongly marked, and also three tests which show such extremely low elongation that it is certain the material was not properly treated, or that there is an error in the records.

CHAPTER XVI.

THE HISTORY AND SHAPE OF THE TEST-PIECE.

SECTION 129.—*Differences in physical properties between the surface and the interior of worked steel.*—The first question that arises in the inspection of steel is the manner in which the test-piece shall be taken. In former days it was the custom to carefully plane or turn a piece to a standard size, with a certain length between shoulders and a certain radius for the terminal fillets; but this method is both tedious and expensive with no corresponding advantages. It is still used in steel castings, for it is impossible to cast a bar of sufficiently accurate section to be fit for a tensile test, and it is also used in the case of forgings where the piece is too large to be broken in full section, and when it is deemed advisable to carve a piece from the finished material. In all other work the test is either a part of the finished bar, as in the case of small rounds and flats, or is cut from the member, as in the case of angles, channels, etc., with two sides of the piece in the condition in which they left the rolls. A sufficient length is taken to allow about 10 inches between jaws, and the readings are made on an 8-inch length which is defined by marks of a center-punch.

A machined piece is generally inferior to a bar as it leaves the rolls. It is true that Table 71 shows no gain in ductility from continued stretching or polishing of the skin, but this is an entirely different matter from the full compression which the outer surface of a bar receives in the last pass. In a series of tests made at Chester, Pa., by the United States Government* in 1885, the machine was not powerful enough to pull a seven-

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* *Report of the Naval Advisory Board on the Mild Steel used in the Construction of the Dolphin, Atlanta, Boston, and Chicago;* 1885, pp. 81, 82.

eighth-inch round, so that rods of this size were turned down to three-quarter inch in diameter. The comparative results are given in Table 84, the figures in each case representing the average of 14 heats which were tested in both diameters.

TABLE 84.

Comparative Physical Properties of ¾-inch Rolled Rounds in their Natural State, and ⅞-inch Rounds of the Same Heats Turned Down to ¾-inch.

Condition of bar.	Ult. strength; pounds per square inch.	Elongation in 8 inches; per cent.	Reduction of area; per cent.
¾ inch natural, ...	65764	27.53	42.7
⅞ inch turned to ¾ inch, ...	65038	25.30	42.0

The pieces cut from the seven-eighth-inch bar are evidently inferior to the three-quarter-inch tests, although it will be shown in Table 94 that the larger bar should give the better elongation. It is probable that the inferiority is due to the removal of the best part of the piece in the operation of turning. This phenomenon is more marked in larger sizes, as will be shown by Table 85, which gives the results on bars cut from forged bridge-pins.

TABLE 85.

Physical Properties of Test-Pieces ¾ inch in Diameter, cut from Forged Rounds.

Size of Ingot, 18x20 inches. Pennsylvania Steel Company, 1893.

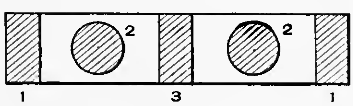
Diameter of forged round.	Place from which test was taken.	Ultimate strength; pounds per square inch.	Elastic limit; pounds per square inch.	Elongation in 8 in.; per cent.	Reduction of area; per cent.	Elastic ratio; per cent.
8 in.	At a depth of 1 inch from outside.	62720	32870	21.50	40.4	52.4
	At a depth of 2 inches from outside.	58100	29170	22.25	37.5	50.2
	The central axis.	58100	31490	20.25	34.1	54.2
10 in.	At a depth of 1 inch from outside.	66070	37080	19.50	33.9	56.1
	At a depth of 2½ inches from outside.	62750	35670	18.00	32.7	56.8
	The central axis.	60900	32140	19.50	23.8	52.8
Preliminary test of same heat from 6 in. ingot		63930	42250	26.25	41.7	66.1

SEC. 130.—*Physical properties of strips cut from eye-bar flats.*—Similar differences will be found if test-pieces be cut from different parts of rolled bars such as are used for making eye-bars. This will be illustrated by Table 86.

These results display considerable uniformity in the higher strength of the test bars which were rolled from the large ingot, but the number of specimens is not sufficient to fully establish the fact. Such a comparison is often invalidated by certain unknown factors, for if the test bar be finished hot and the "flat" cold, the relation may be reversed. Table 87 shows the comparative results on nine heats of steel made at one of our large steel works, and will illustrate how widely the preliminary test may differ from the finished bar in individual cases, while the average of the two is nearly the same. In the light of such facts it seems absurd to reject a heat of steel because the preliminary test falls a few hundred pounds below an arbitrary standard.

TABLE 86.

Physical Properties of Test-Pieces of Different Section Cut from Rolled Flats, together with the Results on ¾-inch Rounds of the Same Heats Rolled from a 14-inch Square Ingot.



1, 1 = edge of bar; 2, 2 = ¾-inch rounds cut on a machine; 3 = center of bar; 4 = ¾-inch round rolled from an ingot.

Number of group.	Limits of ultimate strength in group, of the ¾-inch round rolled from the ingot; pounds per square inch.	Number of heats in group.	Place from which test was taken; see head of table.	Ult. strength pounds per square inch.	Elastic limit; pounds per square inch.	Elastic ratio; per cent.	Elongation in 8 inches; per cent.	Reduction of area; per cent.
I	55000 to 60000	2	1	57450	35085	61.1	28.50	51.97
			2	57095	31575	55.3	27.87	54.43
			3	56990	33185	58.2	25.13	48.89
			4	59463	43489	73.1	27.90	63.01
II	60000 to 65000	6	1	61586	36677	59.6	26.78	48.60
			2	60712	34572	56.9	26.82	53.22
			3	60370	34512	57.2	26.66	44.36
			4	64461	43872	68.1	26.17	50.67
III	70000 to 75000	3	1	63816	38938	61.2	26.72	51.02
			2	64430	35940	55.8	27.37	54.43
			3	62955	37892	60.2	26.38	46.69
			4	70541	47045	66.7	24.51	49.96

SEC. 131.—*Comparison of longitudinal and transverse test-pieces from sheared plates.*—Striking differences may also be found between strips cut lengthwise from a plate and those cut crosswise. In steel imperfectly worked the variation is very marked. Mr. A. E. Hunt, whose opinion is entitled to great weight, states in a private communication that "in plates up to 30 inches wide there is ordinarily a difference of 10 per cent. in tensile strength, and even up to 20 or 25 per cent. in ductility in favor of pieces cut with the grain. In wide plates the difference is not as marked on account of the effect of the cross-rolling."

TABLE 87.

Comparison of Strips Cut from Eye-Bar Flats with the Preliminary Test.

Heat number.	Preliminary test; ¾-inch rolled round; natural.					Longitudinal strip; cut near edge of eye-bar; natural.				
	Elastic limit; pounds per square inch.	Ultimate strength; pounds per square inch.	Elongation in 8 inches; per cent.	Reduction of area; per cent.	Elastic ratio; per cent.	Elastic limit; pounds per square inch.	Ultimate strength; pounds per square inch.	Elongation in 8 inches; per cent.	Reduction of area; per cent.	Elastic ratio; per cent.
1	42220	71820	26.25	53.47	58.8	40710	68830	27.00	47.18	59.1
2	41900	66440	28.25	58.96	63.1	41570	71400	26.25	50.08	58.2
3	41330	69760	25.00	52.94	59.3	39780	69460	25.75	44.31	57.3
4	42440	73640	25.00	55.86	57.6	40880	69400	25.00	48.41	58.9
5	41880	74470	26.25	53.37	56.2	41480	72320	24.50	46.78	57.4
6	43570	72720	24.50	54.48	59.9	41310	73640	23.75	36.54	56.1
7	43210	70240	27.50	58.21	61.5	40370	72060	25.60	40.00	56.0
8	41890	68640	25.00	56.09	61.0	41900	76700	25.75	43.76	54.6
9	42020	69390	28.75	57.14	60.6	41070	69680	27.00	44.33	58 9
Av.	42273	70791	26.28	55.61	59.7	41008	71499	25.62	44.60	57.4

I believe that these differences will be less in plates rolled from a slab than in those made directly from an ingot. In any event, it is quite certain that plates can be made by the first method which exhibit practically the same properties in both directions.

This will be shown by Table 88, which gives the averages of 100 plates which were rolled from Pennsylvania Steel Company slabs by The Paxton Rolling Mills, Harrisburg, Pa. The total number of plates rolled on the order was 104; of these, one was rejected on account of gauge, and three on

account of tensile strength. No plate was thrown out for deficient ductility, although an elongation of 25 per cent. in 8 inches was required in both longitudinal and transverse strips, both these tests being made on each separate plate. The thickness of the plates varied from one-half inch to three-quarter inch, and the width from 52 inches to 87 inches. The steel was basic open-hearth, with an average analysis as follows: Carbon, 0.17 per cent.; phosphorus, 0.014 per cent.; manganese, 0.37 per cent.; sulphur, 0.027 per cent.

TABLE 88.

Comparative Physical Properties of Longitudinal and Transverse Strips from Sheared Plates, rolled by The Paxton Rolling Mills, Harrisburg, Pa., from Pennsylvania Steel Company Slabs.

Composition, per cent.: C, 0.17; P, .014; Mn, 0.37; S, .027.

Average of 100 plates.	Longitudinal.	Transverse.
Ultimate strength; pounds per square inch . .	56960	54540
Elastic limit; pounds per square inch	33350	32260
Elongation in 8 inches; per cent	27.46	27.90
Reduction of area; per cent	51.07	50.87

SEC. 132.—*Comparative physical properties of parallel-sided and grooved test-pieces.*—The United States Treasury Department prescribed the grooved test on marine boiler steels up to the year 1895, but it is well known to be entirely misleading, and the present regulations call for a piece with parallel sides. The relation existing between the two different systems is shown in Table 89, which gives the results obtained by The Lukens Iron and Steel Company, Coatesville, Pa., from duplicate strips cut side by side from the same plate. I am indebted to Mr. A. F. Huston, First Vice-President of the company, for permission to use these records.

TABLE 89.

Comparative Ultimate Strength of the Same Steel in Parallel and Grooved (Marine) Sections.

Thickness of plate in inches.	Number of plates tested.	Average ultimate strength; pounds per square inch.			Reduction of area.	
		Grooved.	Parallel.	Difference.	Grooved.	Parallel.
1	4	65600	53100	12500	52.0	58.0
$\frac{3}{4}$	6	62700	52800	9900	51.4	64.5
$\frac{5}{8}$	5	60900	51100	9500	und.	63.2
$\frac{7}{16}$	4	61300	53500	7800	61.7	65.2
$\frac{3}{8}$	3	60600	54100	6500	60.0	66.5

SEC. 133.—*Effect of shoulders at the ends of test-pieces on the physical properties.*—The flow of force, by which the tensile tests on the grooved section are rendered almost worthless, occurs also in 2-inch test-pieces when there are shoulders at each end. The difference is very much less, but I believe its existence will be shown by the following records. At a certain works it was the custom to cut two tests from one plate of each heat and pull one piece in a section 2 inches long and $1\frac{1}{2}$ inches wide, with shoulders on each end, while the other piece was pulled in a parallel-sided section 8 inches long and 3 inches wide. Table 90 gives the results found by averaging the records of the two kinds of tests.

TABLE 90.

Comparison of the Ultimate Strength of 2-inch Tests with Shoulders, and 8-inch Parallel-Sided Tests, the Two Pieces being Almost Always Cut Side by Side from the Same Plate.

All plates were rolled direct from the ingot at one heat.

Relation of ultimate strength of 2-inch and 8-inch test-pieces.	Difference in ultimate strength between 2-inch and 8-inch test-pieces; pounds per square inch.	Ultimate strength; 50000 to 58000 pounds per square inch; below .04 per cent. phosphorus.			Ultimate strength; 58000 to 64000 pounds per square inch; below .04 per cent. phosphorus.			Total heats.
		$\frac{1}{4}$ to $\frac{3}{8}$ thick.	$\frac{3}{8}$ to $\frac{1}{2}$ thick.	$\frac{1}{2}$ to $\frac{5}{8}$ thick.	$\frac{1}{4}$ to $\frac{3}{8}$ thick.	$\frac{3}{8}$ to $\frac{1}{2}$ thick.	$\frac{1}{2}$ to $\frac{5}{8}$ thick.	
2 inch gave less strength than the 8 inch.	less than 1000	6	10	3	4	7	4	34
	bet. 1000 and 2000	3	4	2	1	1	....	11
	bet. 2000 and 3000	1	3	....	4	2	....	10
	bet. 3000 and 4000	1	....	1	1	3	1	7
	bet. 4000 and 5000	....	2	....	1	....	....	3
	over 5000	....	....	....	3	3	....	6
	Total	11	19	6	14	16	5	71
2 inch gave more str'ngth than the 8 inch.	less than 1000	23	28	4	2	7	4	68
	bet. 1000 and 2000	23	36	4	8	16	6	93
	bet. 2000 and 3000	15	15	3	8	8	4	53
	bet. 3000 and 4000	4	13	5	3	3	....	28
	bet. 4000 and 5000	5	5	2	....	2	2	16
	over 5000	2	15	2	1	2	1	23
	Total	72	112	20	22	38	17	281

It will be a revelation to some engineers that such wide variations can exist in plates, but it will be evident that they are more apt to occur in plates rolled direct from an ingot than in those made from a slab. Including these accidents, the records show that in only 71 plates did the 2-inch test show less tensile strength than the 8 inch, and in half of these

cases the difference was less than 1000 pounds; on the other hand there were 281 cases where the 2-inch test showed greater strength, and the differences are more marked, the largest group showing an increase of from 1000 to 2000 pounds. It will be shown by Table 95 that the width of the piece has very little effect upon the strength, so that these records give evidence of the reinforcement of the 2-inch test from the shoulders at the ends.

SEC. 134.—*Use of the preliminary test-piece as a standard.*—Granting that the test is to be made on a parallel-sided piece, and knowing also, as proven in Section 115, that the results on different-sized bars will be practically uniform as long as they are made from a large ingot and bloom, it has been proposed that the steel be tested by making what is known as a "preliminary test," by which is meant a trial bar, either round or flat, rolled from a small ingot. Mr. A. E. Hunt, of The Pittsburg Testing Laboratory, formerly* advocated this system, but he has recently† changed his opinion.

It is the custom at Steelton to make such a preliminary test on every charge, but this is done merely to classify the metal. If the bar is rolled under proper conditions, its ultimate strength represents the ultimate strength of the finished material, and without regard to any results on elongation or other qualities, the steel is used or laid aside.

We are perfectly willing that the inspectors should see all the results, but we claim that these records have nothing to do with the acceptance or rejection of the material. In other words, this test is our own work while the business of the inspector is to test the material that he buys as fully and carefully as he may wish, without regard to whether a small test ingot has or has not fulfilled certain requirements, or whether it has been made at all.

Our experience in comparing results from the preliminary test with those from the finished material, differs radically from that recorded by Mr. Hunt,‡ although we agree on the

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* *The Inspection of Materials of Construction in the United States. Journal I. and S. I.*, Vol. II, 1890, p. 316.

† See discussion of my paper on *Specifications for Structural Steel. Trans. Amer. Soc. Civil Eng.*, April, 1895.

‡ *Loc. cit.*

important point that the ultimate strength remains nearly constant. Table 91 compares the data obtained from a large number of charges of acid open-hearth steel having a tensile strength between 56,000 and 64,000 pounds per square inch. They were all rolled into angles and the charges are grouped according to the thickness of the finished material.

TABLE 91.

Comparison of Strips, cut from Angles, with the Preliminary Test.

History of test-piece.	No. of heats in average.	Elastic limit; pounds per square inch.	Ultimate strength; pounds per square inch.	Elongation in 8 in.; per cent.	Reduction of area; per cent.
Cut from $\frac{5}{16}$-inch and $\frac{3}{8}$-inch angles	39	41300	60190	28.89	58.0
Rolled from 6-inch test ingot	39	42270	60200	26.44	42.4
Cut from $\frac{7}{16}$-inch and $\frac{1}{2}$-inch angles	46	40170	60660	29.05	56.4
Rolled from 6-inch test ingot	46	43070	61360	25.01	40.0
Cut from $\frac{9}{16}$-inch and $\frac{5}{8}$-inch angles	37	39710	61520	28.96	53.6
Rolled from 6-inch test ingot	37	42090	62930	23.10	38.2

The great inferiority of the tests from the 6-inch ingot is easily explained. It is very difficult to cast small ingots so that they shall not be scrappy, and the bars rolled from them will oftentimes contain flaws ; consequently we break down the ingot to a billet two inches square and chip out the flaws, after which the piece is reheated and gives a perfect bar. It does not receive sufficient work to ensure good elongation, but this is of no consequence, for it is only the strength of the material which is under investigation, and in this respect the results are found to be strictly comparable with the finished material.

SEC. 135.—*Comparative physical properties of rounds and flats.*—It has been mentioned that the properties of a flat bar are different from those of a round, and it will not be unprofitable to investigate the relation.

The points involved are three :

(1) The percentage of work on the piece.
(2) The finishing temperature.
(3) The shape of the piece.

(1) The amount of reduction from the bloom or ingot should not play too great a part in the problem, for it is the duty of the manufacturer to so conduct the operation that every piece, no matter how large, shall have sufficient work. But it must be considered that a large section, a 9-inch round for example, can not possibly be finished under the same thorough and permeative compression that can be put upon a bar only one inch in diameter or upon a thin flat.

(2) It is the business of the rolling mill to so arrange that every piece is rolled at a proper temperature, but it will be recognized as impracticable to finish bars of all diameters and thicknesses under identically the same conditions.

(3) The shape of the test-piece has an influence upon the nature of the results, but it is often difficult to isolate this relation from the effect of work and finishing temperature.

The separation of these three intertwining influences is a complicated problem, the nature of which will be illustrated by Table 92, which gives the results obtained from a large number of heats by cutting two billets from the same ingot and rolling one into a round and the other into a flat.

All the lessons of this table are not written on its face, but an examination discloses the following facts:

(1) Taking into consideration both natural and annealed bars, there are 18 comparisons between rounds and flats. The ultimate strength is less in the flat in every case. The elastic limit falls in 17 cases, and the gain in the exception is slight. The elongation is raised in 16 cases, while in the two exceptions the loss is small. The reduction of area is lowered in 14 cases and raised in four. The elastic ratio is lowered in 15 cases, while in the exceptions the increase is small.

(2) Comparing the loss of strength in passing from round to flat, there are nine possible comparisons between the loss in the natural bar and the loss in the annealed piece. The ultimate strength falls more in every case in the annealed than it does in the natural bar. The elastic limit falls in six cases and rises to a much less extent in three. The elongation rises in five cases and falls in four. The reduction of area falls in all cases. The elastic ratio falls in five cases and rises in four.

It will be found also that the exceptions and irregularities are not confined to any one kind of steel, so that it would

seem proper to average the losses and gains in order to eliminate the errors due to the small number of heats in some of the groups. The results of such condensation are given in Table 93, which shows the true average of all the heats and not the average of the groups.

TABLE 92.

Comparative Physical Properties of $\frac{3}{4}$-inch Rounds and $2\text{x}\frac{3}{8}$-inch Flats Rolled from the Same Billet.

All bars were rolled from a 4x4-inch billet on the same mill.

	Limits of ultimate strength; pounds per square inch.	Kind of steel.	No. of heats in average.	Ult. strength; pounds per square inch.		Elastic limit; pounds per square inch.		Elongation in 8 inches; per cent.		Reduction of area; per cent.		Elastic ratio; per cent.	
				Round	Flat	Round	Flat	Round	Flat	Round	Flat	Round	Flat
Natural bars.	56000 to 60000	Bess.	11	58869	58458	42318	41698	27.75	31.45	58.83	56.13	71.88	71.33
		O. H.	4	58568	58130	40300	40400	29.69	30.13	60.78	61.75	68.81	69.51
	60000 to 64000	Bess.	6	62087	60825	45323	43135	27.04	30.42	55.31	56.20	73.00	70.92
		O. H.	7	62187	62089	42606	42441	28.04	30.14	62.16	60.86	68.51	68.36
	64000 to 68000	Bess.	9	66241	64621	47568	45194	26.08	28.42	50.07	47.80	71.81	69.94
		O. H.	....	....	....	....	....	....	....	....	....	....	....
	68000 to 72000	Bess.	3	70457	69773	50263	49060	24.75	26.67	48.30	48.40	71.34	70.31
		O. H.	2	70530	69420	49000	45000	26.88	25.63	61.10	59.30	69.47	64.96
	72000 to 80000	Bess.	4	77440	76900	53760	52240	24.06	23.44	42.35	40.15	69.42	67.93
		O. H.	12	76616	75865	51108	49691	24.52	24.69	53.73	54.40	66.71	65.50
Same bars annealed.	56000 to 60000	Bess.	11	55703	54194	37828	35603	29.14	30.05	66.55	63.13	67.91	65.70
		O. H.	4	54098	51418	31823	30393	28.75	31.06	62.65	60.50	58.82	59.11
	60000 to 64000	Bess.	6	59372	56192	40570	37542	30.13	30.63	65.50	63.38	68.33	66.81
		O. H.	7	58364	55021	35120	31576	28.61	30.36	63.47	60.00	60.17	57.39
	64000 to 68000	Bess.	9	61694	58838	42228	38476	28.25	28.36	62.91	59.01	68.45	65.39
		O. H.	....	....	....	....	....	....	....	....	....	....	....
	68000 to 72000	Bess.	3	65903	64160	44660	43770	26.08	28.58	63.23	59.50	67.76	68.22
		O. H.	2	65500	60850	37685	34000	23.38	26.50	55.30	52.10	57.53	55.87
	72000 to 80000	Bess.	4	71548	68780	47643	43568	25.81	26.38	57.53	51.00	66.59	63.34
		O. H.	12	69402	67618	40505	39403	23.04	26.31	56.54	51.36	58.36	58.27

It is shown that the loss of ultimate strength from the round to the flat is very much greater in the annealed than in the natural bars, and that the elastic limit more than keeps pace with it, as shown by the elastic ratio. The difference

can hardly be due to the effect of varying work, for the round was reduced to 2.6 per cent. of the area of the billet and the flat to 4.7 per cent., the reduction in both cases being so heavy that the results should be uniform as far as this factor is concerned. The effect of the finishing temperature may be ignored in the case of the annealed pieces, and yet there is a difference of 2448 pounds per square inch in ultimate strength between the flat and round.

TABLE 93.

Comparative Physical Properties of Round and Flat Bars in the Natural and Annealed States.

Average of all heats given in Table 92.	Condition of bar.	Shape of bar.		Gain = + Loss = — in flat.
		Round	Flat	
Ultimate strength; pounds per square inch,	Natural Annealed	66679 62015	65911 59567	—768 —2448
Elastic limit; pounds per square inch,	Natural Annealed	46588 39633	45268 37106	—1320 —2527
Elastic ratio; per cent.,	Natural Annealed	69.87 63.91	68.68 62.29	—1.19 —1.62
Elongation in 8 inches; per cent.,	Natural Annealed	26.48 27.16	28.22 28.73	+1.74 +1.57
Reduction of area; per cent.,	Natural Annealed	54.98 61.98	54.05 58.12	—0.93 —3.86

The natural bars show less difference, which would indicate that the effect of the finishing temperature has raised the strength of the flat more than the round. This is contrary to the condition just noted that the reduction in rolling was less in the case of the flat, but it is in accord with the evident fact that a thin bar would cool faster than a round bar of somewhat less sectional area. The effect of the finishing temperature, therefore, was to raise the tensile strength of the flat more than it did the round, but not enough to overcome the difference in physical properties caused by the shape of the bars.

The reduction of area is less in the case of the flat, and the difference is more marked in the annealed than in the natural bars. The elongation is higher in both kinds of flats than in the corresponding rounds, but the difference is greater in the natural bars. This appears at first sight to be an exception, but on further consideration it will be seen that a decrease in

gain is equivalent to a loss, and this brings it in accord with the decrease in the ductility, as shown by the lessened reduction of area. The net result may be summarized as follows:

(1) Flat bars differ from rounds in having less tensile strength, lower elastic limit, lower elastic ratio, greater elongation, and a slightly lower reduction of area.

(2) This difference is caused not by reason of a different finishing temperature, but in spite of it.

TABLE 94.

Comparative Physical Properties of Rounds of Different Diameters, Rolled from the Same Heats, Made by The Pennsylvania Steel Company.

Each figure is an average of from 4 to 16 determinations.

Heat No.	Ult. strength; pounds per square inch.		Elastic limit; pounds per square inch.		Elongation in 8 inches; per cent.		Reduction of area; per cent.	
	3/4 in.	7/8 in.	3/4 in.	7/8 in.	3/4 in.	7/8 in.	3/4 in.	7/8 in.
11478	60028	58215	40023	39433	29.52	30.63	60.56	60.80
11489	59170	57671	37333	37079	29.81	31.96	63.45	62.31
11550	58223	57707	39219	37482	29.73	30.40	62.70	64.10
11694	57833	58078	39373	38210	32.45	30.75	66.50	62.60
11796	57980	57517	38830	38288	30.14	31.04	60.45	63.50
11945	57456	56753	38498	37268	29.81	30.59	61.60	59.60
12006	57550	55878	38205	36485	29.58	30.58	60.81	65.05
12007	57943	57408	38752	37498	30.38	31.44	64.13	61.10
12519	58774	56106	39015	37485	29.80	31.34	62.40	59.45
2032	59670	56963	39050	36810	29.67	30.50	64.50	57.90
2073	59772	56425	39941	37007	30.25	32.79	64.90	63.70
Av.	58582	57156	38931	37550	30.10	31.09	62.91	61.83
	5/8 in.	3/4 in.	5/8 in.	3/4 in.	5/8 in.	3/4 in.	5/8 in.	3/4 in.
11478	60423	60028	41373	40023	29.44	29.52	65.40	60.56
12007	58120	57943	38200	38752	30.16	30.38	64.55	64.13
1523	59633	55735	42360	38756	30.06	31.66	64.22	65.40
2200	59421	59435	41276	39860	30.00	30.31	64.86	64.65
Av.	59399	58285	40802	39348	29.92	30.47	64.76	63.69
	7/8 in.	1 1/8 in.	7/8 in.	1 1/8 in.	7/8 in.	1 1/8 in.	7/8 in.	1 1/8 in.
12334	57820	59813	37770	37298	30.85	32.25	63.15	61.55
	7/8 in.	1 5/16 in.	7/8 in.	1 5/16 in.	7/8 in.	1 5/16 in.	7/8 in.	1 5/16 in.
12368	62683	60480	39985	36576	30.69	31.97	62.23	53.80
	.....	1 1/4 in.	.....	1 1/4 in.	.....	1 1/4 in.	....	1 1/4 in.
11517	.....	60633	.....	36770	.....	32.02	.....	54.3

SEC. 136.—*Comparative physical properties of rounds of different diameter.*—The variation in strength of bars of the same steel is not by any means confined to pieces of different shape, for it will exist in rounds of different diameters. In Table 94 are given the results on a large number of rivet rods

where several tests were made from the same heat. All the charges were of the same quality of steel, ranging from .11 to .15 per cent. in carbon, .02 to .04 per cent. in phosphorus, and .022 to .038 per cent. in sulphur.

The number of heats given in the table would not be sufficient to justify a general conclusion if there were only a single bar of each heat, but it will be noted that each figure is the average of from 4 to 16 determinations. In the comparison of the three-quarter and seven-eighth-inch rounds there were 112 tests of the smaller size and 94 of the larger, while in the comparison of the five-eighth and three-quarter inch there were 32 tests of the former and 34 of the latter. No average is given where less than four tests were taken of the same size from the same heat.

Comparing the seven-eighth inch with the three-quarter-inch bars, it will be found that in the larger size the following changes occurred:

(1) The ultimate strength was lowered in ten heats and raised in one, the average showing a decrease of 1426 pounds per square inch.

(2) The elastic limit was lowered in all cases, the average showing a decrease of 1381 pounds per square inch; the elastic ratio was reduced from 66.5 per cent. to 65.7 per cent.

(3) The elongation was raised in ten cases and lowered in one, the average showing an increase of 0.99 per cent.

(4) The reduction of area was lowered in seven heats and raised in four, the average showing a decrease of 1.08 per cent.

Comparing the five-eighth and three-quarter inch, it will be found that in the larger size the following alterations have taken place:

(1) The ultimate strength was lowered in three heats and raised a trifling amount in one, the average showing a decrease of 1114 pounds per square inch.

(2) The elastic limit was lowered in three cases and raised in one, the average showing a decrease of 1454 pounds per square inch; the elastic ratio was reduced from 68.7 per cent. to 67.5 per cent.

(3) The elongation was raised in every case, the average showing an increase of 0.55 per cent.

(4) The reduction of area was lowered in three heats and raised in one, the average showing a decrease of 1.07 per cent.

The consistent testimony of these records is corroborated by the data on the larger diameters. It is true that only one heat is given on each of these sizes, but it so happens that there were from twelve to sixteen bars in each case, and as the steel was of the same manufacture in all particulars the results may be accepted as fairly comparable. It seems quite certain that larger bars will give a lower ultimate strength, a lower elastic limit, a lower elastic ratio, a better elongation, and a lower reduction of area. Some of these characteristics may be due to differences in finishing temperature, but the data on elastic limits show that the pieces were all rolled at nearly the same degree of heat, and such small variations, even if due entirely to rolling conditions, are not sufficient to account for the increase in the elongation.

This subject of variation in physical qualities, as produced by differences in diameter, has been discussed by Appleby.* In common with many others, he makes the vital and fundamental mistake of rolling all the bars to one size, *viz.:* 1½ inches in diameter, and turning the test specimens from these bars. It will be evident that a test-piece of one-half inch in diameter thus obtained will be merely the core or center of the original bar, and will be inferior both chemically and physically. On the one hand it embraces the area of maximum segregation, while on the other it has not undergone the thorough compression that the exterior of the bar has received in the rolls or under the hammer, and a comparison of the bars is therefore invalid.

The method, which I have employed in this section, of comparing rolled bars of different sizes in the form in which they left the rolls, also presents some complicating conditions, inasmuch as the effect of work is not the same on large and on small sections, but it has the overwhelming advantage that it represents actual conditions, and portrays the exact results that may be expected in practice.

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* *Proc. Inst. Civil Eng.* (England), Vol. CXVIII, pp. 395-417.

SEC. 137.—*Influence of the width of the test-piece upon the physical properties.*—Conclusive testimony that variations in the elongation may be due solely to the cross-section of the test-piece is furnished by Table 95, which gives the results obtained in breaking strips of different width when the pieces were cut side by side from the same plate.

TABLE 95.

Effect of Changes in the Width of the Test-Piece upon the Physical Properties.

	Thickness in inches.	No. of heats in av.	Width of test-piece in inches.					
			3	2	1½	1	¾	½
Ultimate strength; pounds per square in.	5/8	2	72510	73480	73840	73250	74420	75440
	9/16	8	72020	72220	72420	72643	71563	73531
	1/2	8	67945	68500	68710	68220	68050	68940
	7/16	2	73840	73550	74530	73370	73520	76130
	3/8	10	68111	68224	67950	67890	68338	67442
	True av.	30	69784	70039	70176	69968	69872	70578
Elastic limit; pounds per square in.	5/8	2	. . . . .	41685	42185	41965	42975	46655
	9/16	8	. . . . .	42485	42353	42711	42798	46058
	1/2	8	. . . . .	41600	42190	41620	41630	45820
	7/16	2	. . . . .	45840	46740	46085	46285	51820
	3/8	10	. . . . .	45939	45346	45664	46676	45659
	True av.	30	. . . . .	43571	43588	43579	44023	46285
Elongation in 8 inches; per cent.	5/8	2	29.87	28.87	28.37	25.00	23.75	24.25
	9/16	8	29.78	27.88	27.66	26.06	24.78	24.88
	1/2	8	30.75	28.69	27.72	27.34	26.31	24.03
	7/16	2	28.37	27.50	25.62	25.87	25.12	23.50
	3/8	10	28.50	27.23	26.65	25.85	24.98	22.93
	True av.	30	29.52	27.92	27.25	26.25	25.21	23.87
Reduction of area; per cent.	5/8	2	52.7	56.1	56.3	53.6	52.3	56.0
	9/16	8	53.7	54.2	57.3	57.2	57.6	58.9
	1/2	8	56.8	58.9	59.9	59.6	59.7	61.0
	7/16	2	52.1	53.9	56.8	60.0	58.2	56.1
	3/8	10	55.0	56.2	57.9	58.8	59.5	60.0
	True av.	30	54.79	56.23	58.09	58.32	58.48	59.45

It must be kept in mind that no comparison can be made between the different thicknesses, since the individual heats were not the same. In the matter of widths, however, the case is otherwise, for every heat in the group was tested in all the widths, the bars from each heat being cut from the same small strip of plate, and this should give a perfectly valid basis of comparison.

The conclusions which must be drawn from the table are as follows:

(1) Variations in the width of the test-piece have very little effect upon the ultimate strength per square inch.

(2) They probably have little influence upon the elastic limit. The narrowest pieces show a decided increase, but this needs corroboration. The three-inch pieces were pulled at the works of the Pottstown Iron Company, being beyond the capacity of the machine at Steelton, and the determinations of elastic limit are therefore not comparable.

(3) The elongation increases regularly as the width increases.

(4) The reduction of area decreases regularly as the width increases.

The same subject was investigated by Barba,* his results being given in Table 96.

TABLE 96.

Influence upon the Elongation of Changes in the Width of the Test-Piece (Barba).

Number of sample.	Dimensions in inches.			Ratio of width to thickness.	Elongation; per cent.
	Length.	Width.	Thickness.		
1	3.94	0.394	0.394	1	31.0
2	3.94	0.787	0.394	2	34.0
3	3.94	1.181	0.394	3	35.0
4	3.94	1.575	0.394	4	37.2
5	3.94	1.964	0.394	5	39.0
6	3.94	2.352	0.394	6	40.8
7	3.94	2.756	0.394	7	38.5
8	3.94	3.150	0.394	8	34.5

The figures seem to show a continual increase in elongation until the width is six times the thickness, after which the stretch grows less. This latter point is not an important matter in practice since there is no occasion to use such a wide section, and in the case of plates of ordinary thickness the strength of such pieces is beyond the capacity of most machines.

The increase in elongation in greater widths has also been shown by E. A. Custer, of the Baldwin Locomotive Works, Philadelphia, Pa., who has given me in a private communication the results obtained by him in testing strips from boiler plate.

* *Résistance des Matériaux; Mémoires de la Société des Ingénieurs Civils.* Vol. I, 1880, p. 682.

The steel ranged in ultimate strength from 55400 to 61300 pounds per square inch, and was of nearly uniform chemical composition. The records are given in Table 97.

TABLE 97.

Effect of an Increase of Width upon the Elongation.*

Thickness in in.		Width of piece in inches.				
		1	1¼	1¾	2¼	3
½	Number of pieces	180	120	30	30	18
	Average ultimate strength; lbs. per sq. inch	57950	57878	58102	57800	57675
	Elongation in 8 inches; per cent.	26.27	26.98	28.01	29.49	30.82
¾	Number of pieces	20	25	20	20	20
	Average ultimate strength; lbs. per sq. inch	56680	57001	56720	56860	55870
	Elongation in 8 inches; per cent.	26.92	26.96	27.91	30.17	31.02

SEC. 138.—*Influence of a change in length upon the physical properties.*—In order to determine the relative elongation with varying length, I have carried out the following investigation: Twenty rods, three-quarter inch in diameter, were selected from one heat of acid open-hearth steel. From each rod seven bars were cut, one of which was tested in a length of 2 inches, and one each in 4, 6, 8, 10, 12, and 14 inches. The results are given in Table 98. The individual records of elongation are shown to prove that the averages are not formed by the combination of unlike members. These data are plotted in Curve *AA*, Figure XV.

A similar series of tests was made by Barba,† the results being given in Table 99, and plotted in Curve *BB*, Figure XV.

The linear elongation of a fractured bar is made up of two factors. First, the excessive stretch in the immediate neighborhood of the break, due to the deformation known as "necking." Second, the "permanent set" which occurs throughout the rest of the bar. It will be plain that the first factor will bear a greater ratio to the sum total as the length grows less, while it will bear a less ratio as the length increases. It will therefore follow that if the length of the piece is reduced so that it is all included in the region of necking, as, for instance, when the piece is only 2 inches

* E. A. Custer, private communication.

† *Résistance des Matériaux; Mémoires de la Société des Ingénieurs Civils.* Vol. I, 1880, p. 682.

long, the percentage of elongation will increase rapidly. On the other hand, when the length in increased beyond 14 inches, the ratio of the first factor to the second is not great and consequently the change in total percentage with each linear increment is not marked.

Table 98.

Influence upon the Physical Properties of Changes in the Length of the Test-Piece.

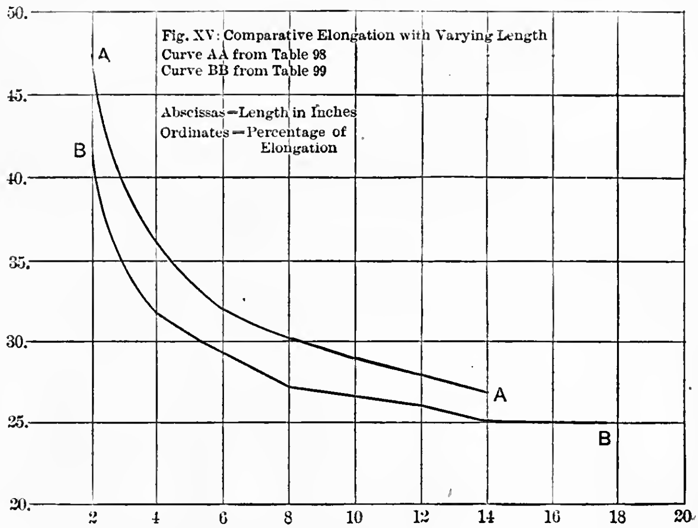
¾-inch rounds; Pennsylvania Steel Company acid open-hearth rivet steel.

	No. of bar.	Length of test-piece in inches.						
		2	4	6	8	10	12	14
Ult. strength; lbs. per square inch.	Av.	60685	60343	60099	60123	60068	60059	60066
Elastic limit; lbs. per square inch.	Av.	42548	43134	42951	43159	43161	43024	43234
Elastic ratio; per cent.	Av.	70.11	71.48	71.47	71.78	71.85	71.64	71.98
Reduction of area; per cent.	Av.	66.7	66.9	67.1	66.8	67.3	67.2	67.1
Elongation; per cent.	1	47.50	35.00	30.67	30.50	28.20	27.17	26.43
	2	46.00	35.50	30.67	30.50	29.80	27.67	26.43
	3	47.00	34.50	32.33	28.25	27.80	27.50	26.43
	4	48.50	35.50	32.00	30.25	28.20	25.00	27.00
	5	47.00	35.50	33.00	28.75	29.00	27.17	28.14
	6	46.50	39.00	32.67	28.75	31.60	29.33	23.21
	7	47.50	37.50	31.33	30.50	29.40	27.33	25.71
	8	46.00	33.00	30.00	30.00	26.60	28.00	24.43
	9	47.50	35.50	34.33	31.75	30.40	29.33	28.21
	10	47.50	36.00	30.33	29.50	28.80	28.50	25.29
	11	49.00	34.75	30.00	31.00	30.20	27.75	27.57
	12	49.00	36.50	31.33	29.50	27.80	29.83	28.71
	13	47.00	35.50	32.33	29.00	26.60	27.00	26.43
	14	47.50	38.00	31.67	32.75	31.00	30.50	26.79
	15	48.50	37.00	33.33	30.75	29.00	28.33	27.64
	16	47.50	37.00	33.00	31.25	31.00	27.75	29.29
	17	48.50	37.00	32.50	29.00	28.20	27.33	27.21
	18	46.00	35.00	34.67	28.75	28.00	28.75	25.86
	19	47.00	37.00	33.00	30.00	27.50	27.00	26.29
	20	47.50	37.50	34.33	32.50	30.00	26.25	28.14
	Av.	47.43	36.11	32.17	30.16	28.96	27.87	26.76

If the length were zero the percentage of elongation would be infinite, while if the length were infinite the percentage of extension would be represented by the permanent set of those portions of the bar where no necking occurs. The true curve therefore expressing the law of relative elongation is undoubtedly an hyperbola, one asymptote of which will correspond to a length of zero, while the other will be the percentage due to the permanent set, which will vary with every kind of steel.

I had thought it possible to deduce the law of elongation for all lengths by expanding the data in Figure XV by the methods of analytic geometry. It is well known that any five

points, no matter how situated, may be included in the line of a conic section, and it would seem possible, therefore, to select five points in either curve and deduce their equation, which could then be expanded indefinitely.



Construction points.				
No.	Curve AA.		Curve BB.	
1	x = 2	y = 47.43	x = 1.97	y = 42.0
2	x = 4	y = 36.11	x = 3.94	y = 32.0
3	x = 6	y = 32.17	x = 5.91	y = 29.3
4	x = 8	y = 30.16	x = 7.87	y = 27.2
5	x = 10	y = 28.96	x = 9.84	y = 26.6
6	x = 12	y = 27.87	x = 11.81	y = 26.0
7	x = 14	y = 26.76	x = 13.78	y = 25.1
8	. . . .	. . . .	x = 15.75	y = 25.0
9	. . . . . .	. . . . .	x = 17.72	y = 24.9

Fig. XV.—Curves Showing Law of Elongation with Varying Length.

The application of this method to points 1, 2, 3, 5, and 7 in Curve *AA* in Figure XV, derived from Pennsylvania Steel Company steels, gives Curve *AA* in Figure XVI. The line is very far from the truth, for it indicates only 65 per cent. elongation for a length of zero, and an elongation of zero for a length of 73 inches.

Curve *BB* in Figure XVI represents the result of expanding points 1, 3, 5, 7, and 9 in Curve *BB*, Figure XV, derived from Barba's work. It will be noted that point 1 of this

curve, where $x=1.97$ and $y=42.0$, as shown in Table 99, is on the upper and return side of the ellipse, and this fact may be taken as proof by *reductio ad absurdum* that the method is inapplicable to the expanding of such functions into extra-experimental territory. It is deemed pertinent, however, to place this investigation on record to show that the determinative errors in the most carefully constructed records are sufficient to destroy the value of this mathematical calculation, which seems at first sight to be logically correct.

TABLE 99.

Influence upon the Elongation of Changes in the Length of the Test-Piece.*

No. of bar.	Dimensions; inches.		Ratio of length to diameter.	Elongation; per cent.
	Length.	Diameter.		
1	1.97	0.677	2.91	42.0
2	3.94	0.677	5.81	32.0
3	5.91	0.677	8.72	29.3
4	7.87	0.677	11.60	27.2
5	9.84	0.677	14.50	26.6
6	11.81	0.677	17.40	26.0
7	13.78	0.677	20.30	25.1
8	15.75	0.677	23.30	25.0
9	17.72	0.677	26.20	24.9

The percentage of elongation in the portion of the piece which does not undergo "necking" may be calculated from the records in Table 98. As a matter of experience it is found that a length of about two inches includes the region wherein necking occurs, and this length is a constant, no matter what the total length of the test-piece may be. In other words, a test-piece two inches long is practically all "neck," while in one four inches long there will be one length of two inches which is all neck, and another length of two inches which will remain nearly a true cylinder after fracture.

In the case of the 2-inch test-pieces, given in Table 98, the average elongation was 47.43 per cent., representing a linear elongation of 0.9486 inches. In the case of the 4-inch test-pieces the stretch, by the above assumption, was the same in the necked region, while the total elongation was 36.11 per cent., representing a linear elongation of 1.4444 inches. Hence the elongation in the two inches of the cylindrical

* Barba, *Proc. French Soc. Civil Eng.*, Vol. I, 1880, p. 682.

portion was 1.4444 — 0.9486 = 0.4958 inches, or 24.79 per cent.

In the same manner the elongation in the cylindrical portion may be calculated for all the different lengths given in Table 98. The results are as follows, in per cent.:

4″ = 24.79; 6″ = 24.54; 8″ = 24.40; 10″ = 24.34; 12″ = 23.96; 14″ = 23.32.

It will be seen that there is a decrease in elongation with an increase in length, and the relation is so regular that it is probably due to something besides experimental error. If the necking be assumed to take place within a length of only one inch, instead of two inches, the calculated percentage of elongation will be a little more uniform, but the improvement is so slight, even with this extreme hypothesis, that some other cause is shown to be at work.

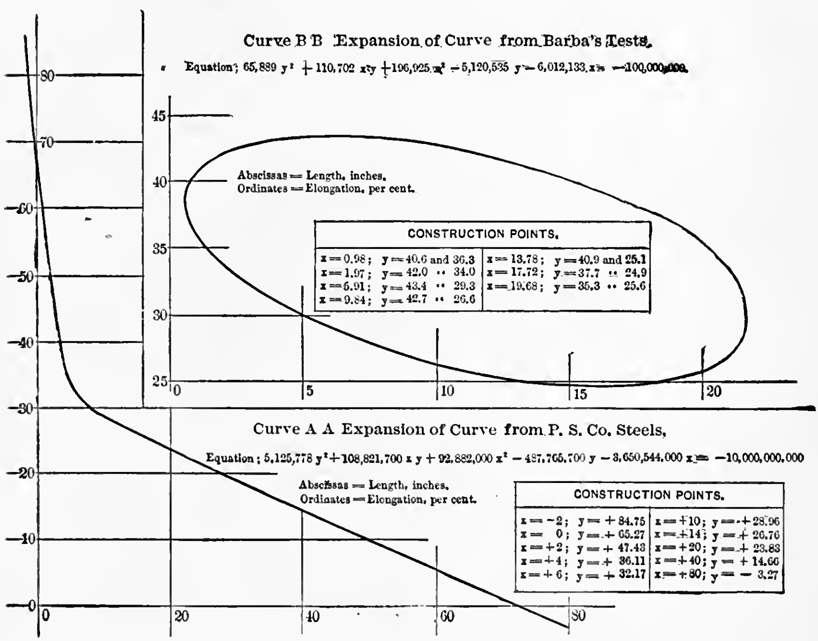


FIG. XVI.—EXPANSION OF CURVES IN FIG. XV.

I believe that the true explanation is in the fact, which was called to my attention by Mr. W. R. Webster, that the breaking speed varies with each length. The speed of the machine was the same in every case, but a moment's consid-

eration will show that a constant speed of the grips does not mean a constant rate of distortion in the bar. In the case of the 2-inch piece the stretch was 47.43 per cent., indicating a linear extension of 0.95 inches; in the case of the 14-inch piece the stretch was 26.76 per cent., indicating an extension of 3.75 inches. The rate of distortion, therefore, was nearly four times as great in the 2-inch test as in the 14-inch bar, and this condition would give a slightly higher elongation with each decrease in length, as shown in Section 142.

Owing to this complication it is impossible to deduce a theoretically accurate answer from the foregoing data, but it may be considered as practically demonstrated that in a three-quarter-inch round bar of infinite length, of the same steel as shown in Table 98, the elongation would be about 24 per cent.

SEC. 139.—*Tests on eye-bars.*—Through the courtesy of The Union Bridge Company, Athens, Pa., I have had access to its records of eye-bar tests, and have classified them in various ways to determine the influence of width, thickness, and length upon the physical properties. The steel was made by different manufacturers, and it was necessary to divide the bars on that basis. Some works were represented by such a small number of bars that it was thought best to omit them from the list as well as the bars from a foreign works which gave results quite inferior to those of domestic manufacture. There were also cancelled all bars which showed 100 per cent. crystalline fracture, and pieces of miscellaneous lengths when there were less than three bars of the same steel in the group. A few pieces were discarded when the percentage of elongation in 12 inches was the same as in the full length, for this indicates either a clerical error or that fracture took place in the eye.

After these eliminations it was found that only three works were represented, two of them by both open-hearth and Bessemer steel. The records are given in Table 100, and they show that there is no radical difference in the character of the metal furnished by the three makers, or between the two methods of manufacture. This does not disprove the statement already emphasized that Bessemer metal is more

Table 100.

Physical Properties of Eye-Bars, Classified According to Method of Manufacture, Name of Maker, Thickness, Width, and Tensile Strength.

NOTES.—The bar was broken in full-sized section, but the elongation here given is the percentage in the 12 inches which included the fracture. "Narrow" signifies not over 6 inches wide, the average being about 5 inches; "Wide" signifies over 6 inches wide, the average being about 7 inches. "Thin" signifies under $1\frac{1}{2}$ inches thick, the average being about 1 inch. "Thick" signifies not less than $1\frac{1}{2}$ inches thick, the average being about $1\frac{7}{8}$ inches.

Name of maker.	Method of manufacture.	Limits of ultimate strength in group; pounds per square inch.	Relative thickness of piece.	Relative width of piece.	Number of heats in average.	Average ultimate strength; pounds per square inch.	Average elastic limit; pounds per square inch.	Average elastic ratio; per cent.	Elongation in 12 inches; per cent.	Reduction of area; per cent.
A	Open-hearth.	51000 to 64000	Thin	Narrow	109	61528	39017	63.4	34.72	49.6
				Wide	18	59950	37937	63.3	38.72	48.6
			Thick	Narrow	33	60838	37470	61.9	37.43	50.0
				Wide	11	60307	36688	60.8	39.61	46.3
		64000 to 74000	Thin	Narrow	72	66702	41967	62.9	32.58	47.5
			Thick	Narrow	19	66570	41853	62.9	34.22	47.5
	Bessemer.	54000 to 64000	Thin	Narrow	102	59557	36086	60.6	34.43	50.3
				Wide	5	61988	38706	62.4	36.20	44.2
			Thick	Narrow	19	60855	36166	59.4	34.16	47.8
				Wide	26	60932	37019	60.8	37.96	48.1
		64000 to 74000	Thin	Narrow	22	66441	41665	62.7	31.93	47.3
				Wide	6	66947	39330	58.7	32.43	45.0
			Thick	Narrow	3	67370	37103	55.1	30.90	42.6
				Wide	3	67263	37290	55.4	33.00	41.8
B	Bessemer.	54000 to 64000	Thin	Narrow	47	59379	35395	59.6	34.08	49.2
				Wide	19	58582	35141	60.0	37.47	47.8
			Thick	Narrow	18	59355	34162	57.6	34.83	46.4
				Wide	61	59536	34403	57.8	36.63	46.4
		64000 to 74000	Thin	Narrow	21	66231	40756	61.5	30.19	47.7
				Wide	5	67184	40766	60.7	35.76	49.3
			Thick	Wide	22	66874	37880	56.6	33.02	45.0
	Open-hearth.	54000 to 64000	Thin	Narrow	103	59018	33901	57.4	33.79	48.8
				Wide	23	59950	32650	54.5	36.65	44.8
			Thick	Narrow	24	58985	33460	56.7	34.80	46.6
				Wide	55	58154	31971	54.7	39.22	48.0
		64000 to 74000	Thin	Narrow	23	66230	40332	60.9	30.13	44.7
				Wide	3	69350	39506	57.0	30.80	36.3
			Thick	Narrow	3	65690	38427	58.5	33.50	44.7
C	Open-hearth.	54000 to 64000	Thin	Narrow	121	60553	35592	58.8	33.57	48.7
				Wide	18	59366	34053	57.4	36.53	46.1
			Thick	Narrow	20	60870	34440	56.6	35.20	48.2
				Wide	21	60240	33245	55.2	39.07	46.2
		64000 to 74000	Thin	Narrow	81	66515	39206	58.9	32.06	46.2

treacherous in service under continued shock, and that therefore it should never be used in bridge eye-bars, but it does serve the purpose of this investigation in allowing the averaging of all the records in order to increase the number of members in each group and thereby eliminate determinative errors.

TABLE 101.

Physical Properties of Eye-Bars, Classified According to Length, Width, and Thickness.*

Kind of bar.	Number of group.	Number of heats in group.	Limits of length of pieces in group; feet.	Average length of group; feet.	Average ultimate strength; pounds per square inch.	Average elastic limit; pounds per square inch.	Elongation in full length; per cent.	Elongation in the 12 in. including the fracture; per cent.	Reduction of area; per cent.
Narrow and thin; 54000 to 64000 pounds per square inch.	1	65	13 to 16	14.8	60070	35890	18.56	34.55	48.97
	2	132	17 to 20	18.6	59950	36160	16.17	33.93	49.40
	3	118	21 to 25	22.7	60280	35940	15.56	34.38	48.81
	4	82	26 to 30	28.1	60140	36530	15.26	34.25	49.95
	5	71	31 to 35	33.2	60120	35990	13.81	33.81	50.11
	True av. A	468	all lengths	. .	60110	36100	. . .	34.17	49.40
Wide and thin; 54000 to 64000 pounds per square inch.	6	15	13 to 16	14.8	59380	35730	17.53	37.58	46.75
	7	21	17 to 20	19.0	59050	34070	17.18	36.79	45.12
	8	22	21 to 25	22.8	60860	35540	15.92	36.00	45.81
	9	14	26 to 30	28.1	58390	33930	14.94	39.61	47.89
	True av. B	72	all lengths	. . .	59540	34840	. . .	37.26	46.21
Narrow and thick; 54000 to 64000 pounds per square inch.	10	38	17 to 20	17.9	60050	35770	17.36	35.94	48.17
	11	38	21 to 25	22.8	61080	36040	15.87	34.46	46.79
	12	17	26 to 30	28.0	57730	32380	15.38	36.83	49.28
	True av. C	93	all lengths	. . .	60050	35260	. . .	35.50	47.80
Wide and thick; 54000 to 64000 pounds per square inch.	13	18	10 to 13	12.0	59708	35130	19.30	35.90	46.10
	14	22	13 to 16	14.8	59460	33990	16.90	38.02	47.97
	15	24	17 to 20	18.9	58930	33080	17.09	38.26	45.92
	16	67	21 to 25	23.2	59990	34270	15.98	37.42	46.94
	17	32	26 to 30	27.8	59360	34330	15.84	39.98	48.05
	18	11	31 to 35	33.1	58480	32090	16.50	40.61	48.15
	True av. D	174	all lengths	. . .	59540	34030	. . .	38.13	47.12
Narrow and thin; 64000 to 74000 pounds per square inch.	19	25	13 to 16	14.7	66590	40830	16.06	31.68	47.12
	20	58	17 to 20	18.5	66620	40420	15.32	31.57	46.19
	21	64	21 to 25	22.9	66230	40730	14.91	32.38	46.84
	22	33	26 to 30	28.7	66150	40590	14.09	32.37	46.36
	23	34	31 to 35	33.1	66560	40620	14.50	30.78	47.55
	True av. E	214	all lengths	. . .	66420	40620	. . .	31.82	46.74

The result of such combination will be found in Table 101, wherein all pieces of the same length and section are added together without regard to method of manufacture or name of maker. The number of bars given does not agree in each

* See notes to Table 100.

case with the number given in the previous list. Thus Table 100 shows 83 bars that are classed as "wide and thin" and as having a tensile strength between 54000 and 64000 pounds, while Table 101 gives only 72 bars. This arises from the fact that some of the 83 bars were shorter than 13 feet or longer than 30 feet, and that there was not a sufficient number of any one size to warrant combining them to make an average. It is evident that the elongation in 12 inches and the reduction of area will be quite independent of the length of the bar, so that each of the divisions is again summarized in the true averages A, B, C, and D. The influence of width will be found by comparing A with B, and C with D, and the influence of thickness by comparing A with C, and B with D.

It is shown that the average elongation in 12 inches of the wider bars is about 3 per cent. better than the narrow pieces, while the narrow bars are superior in reduction of area. It is also indicated that the thick bars give about one per cent. more elongation, but that the difference in thickness does not seem to have a marked or regular effect upon the reduction of area.

The differences are not extreme in any case, and it is always unsafe in such investigations to formulate general laws from an average which may be the combination of positive and negative values, but by analyzing the individual records of the table it will be seen that corroborative evidence is at hand of the correctness of the averages. Referring to the groups by the numbers in the first column, there are seven comparisons for width, *viz.:* 1 to 6, 2 to 7, 3 to 8, 4 to 9, 10 to 15, 11 to 16, 12 to 17; there are seven comparisons for thickness, *viz.:* 2 to 10, 3 to 11, 4 to 12, 6 to 14, 7 to 15, 8 to 16, 9 to 17.

Inspection shows that in every case the wider and the thicker pieces gave the greater elongation in 12 inches. The narrow pieces gave the better reduction of area in every case except one, and in this instance the difference was trifling. In thickness the results on reduction of area are contradictory, there being three cases where the thin bars were superior and four cases where the thick were better. It seems quite certain that either an increase in width or an increase in thickness improves the elongation in the 12 inches that includes the fracture, but that the reduction of area is improved in much less measure or not at all.

Applying the same method of inspection to the records of elongation in full length, it will be found that the wide bars were superior in four cases and inferior in three cases, while the thick bars were superior in five cases and inferior in two cases. Thus there seems to be quite a difference between the records of full-length tests and those from 12-inch lengths, so that it is justifiable to conclude that while wider and thicker bars do give greater elongation after fracture, the advantage is confined to the region of the "necking," and the percentage of stretch throughout the body of the bar is independent of the section. If this is true, it is a most important fact and has a wide application in structural engineering.

TABLE 102.

Physical Properties of Eye-Bars, Classified According to Length; Being the Same Bars Referred to in Tables 100 and 101.

Number of heats in group.	Limits of length in group; feet.	Average length of group; feet.	Average ultimate strength; pounds per square inch.	Average elastic limit; pounds per square inch.	Elongation in full length; per cent.	Elongation in the 12 inches including the fracture; per cent.	Reduction of area; per cent.
41	10 to 12	11.8	59880	35240	18.07	34.68	46.95
102	13 to 16	14.8	59830	35460	18.05	35.75	48.43
215	17 to 20	18.6	59770	35540	16.58	35.04	48.37
245	21 to 25	22.9	60380	3546C	15.75	35.37	47.72
145	26 to 30	28.0	59520	35310	15.37	36.36	49.25
82	31 to 35	33.1	59900	35470	14.17	34.73	49.85
830	all lengths	. . . . .	59930	35440	. . . . .	35.41	48.42

Since it has been thus shown that there is very little, if any, difference in the percentage of elongation in pieces of the same length, although they be of different section, it becomes possible to further combine the records by putting together all widths and thicknesses and classifying by length alone. This is done in Table 102. It may be noticed that there are 41 bars running between 10 and 12 feet in length, while in Table 101 there are only 18 of this size. This arises from the fact that there were a few of this length in each of the groups as classified by section, but they were not in sufficient number to be of value for comparison except in the case of Group 13 (see Table 101). In Table 102 these scattering bars are combined with those of Group 13 in order to have a larger

number in the average. The results are plotted in Figure XVII, which thus shows the law of elongation in long bars. A further point to be considered is the proportion of bars that fall below a given standard, since an average may be made up of widely different kinds of metal or it may be made from a uniform product. In Table 103 is given an analysis of the records showing the number and percentage of bars in each division which give less than a certain percentage of elongation.

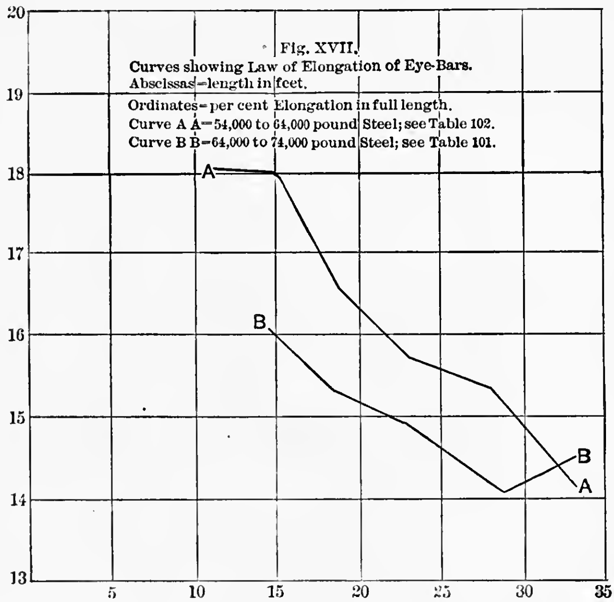


Fig. XVII.—Curves Showing Law of Elongation of Eye Bars.

The standards assumed are those which are specified for different grades of structural steel in Chapter XVIII. A study of the table will show that the number of rejections on longer lengths is fully as great as with the shorter bars, and this proves that the decrease in the specified elongation for an increase in length is not greater than should justly be allowed. In the bars made by "*A*" the rejections under Specification I amount to four per cent. in Bessemer metal, and 10 per cent. in open-hearth; in those

TABLE 103.

Proportion of Rejections Caused by Applying a Standard Sliding Scale of Elongation to the Eye-Bar Records in Table 100.

NOTE.—The standards assumed are the same as specified for different classes of metal in Section 172.

	Name of maker.		"A."						"B."						"C."			Total for all kinds.		
	Kind of steel.		Bessemer.			Open-hearth.			Bessemer.			Open-hearth.			Open-hearth.					
	Length of bars; in feet.	Standard of elongation; per cent.	No. of bars.	No. below standard.	Per ct. below standard.	No. of bars.	No. below standard.	Per ct. below standard.	No. of bars.	No. below standard.	Per ct. below standard.	No. of bars.	No. below standard.	Per ct. below standard.	No. of bars.	No. below standard.	Per ct. below standard.	No. of bars.	No. below standard.	Per ct. below standard.
Specification I. Ultimate strength, 54000 to 64000 pounds per square inch. (See Class VI, Section 172.)	10 to 20	14.0	64	4	. .	82	10	. .	58	1	. .	60	10	. .	105	24	. .	369	49	13
	21 to 25	13.0	47	0	. .	37	3	. .	43	6	. .	85	16	. .	33	1	. .	245	26	11
	26 to 30	12.5	34	1	. .	22	0	. .	33	3	. .	39	8	. .	17	7	. .	145	19	13
	31 to 35	12.0	26	2	. .	11	2	. .	11	5	. .	21	7	. .	25	9	. .	94	25	27
	Total, all lengths,		171	7	4	152	15	10	145	15	10	205	41	20	180	41	23	853	119	14
Specification II. Ultimate strength, 64000 to 74000 pounds per square inch. (See Class VIII, Section 172.)	10 to 20	12.5	30	0	. .	14	2	. .	10	0	. .	10	5	. .	38	10	. .	102	17	17
	21 to 25	12.0	36	1	. .	16	2	. .	23	3	. .	7	4	. .	17	6	. .	99	16	16
	26 to 30	11.5	11	0	. .	4	0	. .	11	2	. .	6	3	. .	10	1	. .	42	6	14
	31 to 35	11.0	14	0	. .	. .	. .	. .	4	0	. .	6	0	. .	16	1	. .	40	1	3
	Total, all lengths,		91	1	1	31	4	12	48	5	10	29	12	41	81	18	22	283	40	14

made by "B" they are 10 per cent. in the Bessemer and 20 per cent. in the open-hearth, while with "C" they are 23 per cent. Taking into consideration that the records cover

only the products of large and well-known works, and that all bars having a crystalline fracture and those breaking in the eye were discarded, it must be acknowledged that the standard calls for good material.

SEC. 140.—*Alterations in the physical properties of steel by rest after rolling.*—In addition to the variations which may be caused by differences in the working of the test-piece and in its shape, there is probably another factor in the length of time which elapses between rolling and testing. This subject was investigated at The Pennsylvania Steel Works by E. C. Felton,* General Manager of the Company, a condensation of

TABLE 104.

Alteration in the Physical Properties of Steel by Rest after Rolling.†

		Hand rounds.						Guide Rounds.					
		No. of bars tested.		Alteration. Gain = + Loss = —				No. of bars tested.		Alteration. Gain = + Loss = —			
Number of group.	Limits of ultimate strength; pounds per square inch.	Less than 24 hrs. rest.	More than 24 hrs. rest.	Elastic limit; pounds per square inch.	Ultimate strength; pounds per square inch.	Elongation in 8 inches; per cent.	Reduction of area; per cent.	Less than 24 hrs. rest.	More than 24 hrs. rest.	Elastic limit; pounds per square inch.	Ultimate strength; pounds per square inch.	Elongation in 8 inches; per cent.	Reduction of area; per cent.
I	55000 to 60000	.	.	. . . .	. . .	. . . .	. . . .	6	10	+719	+437	+.65	+ .96
II	60000 to 65000	10	5	—1207	+385	+1.11	+2.14	10	22	—453	+596	+.73	+1.13
III	65000 to 70000	32	12	— 471	—180	— .25	+2.07	22	36	—170	+382	+.33	+1.45
IV	70000 to 75000	21	20	+ 302	+197	+ .66	+2.95	24	36	—166	+638	+.44	+1.14
V	75000 to 80000	10	8	— 809	+107	+1.06	+6.76	35	47	—314	+201	—.81	+2.33
VI	80000 to 85000	7	3	+ 213	+ 36	+ .29	+ .44	16	30	—165	+767	+.42	+1.24
VII	85000 to 90000	.	.	. . . .	. . .	. . . .	. . . .	8	16	+ 92	+525	+.46	+ .62
Av. of all tests.		80	48	— 394	+109	+ .56	+2.87	121	197	—270	+507	+.32	+ .99

whose work is given in Table 104. The changes are not very strongly marked, but there seems to be consistent testimony of a molecular rearrangement, progressing for several hours after the bar is thoroughly cold, whereby there is a lowering of the elastic limit, and an increase in the ultimate strength, the elongation, and the reduction of area.

*† *Notes on Results Obtained from Steel Tested Shortly after Rolling. Amer. Soc. Mech. Eng.*, Vol. IX, p. 38.

SEC. 141.—*Probable error in current practice in determining the physical properties.*—It is the rule in most practical work that at least two sides of the test-piece are not machined, and hence it is impossible to make a perfectly accurate measurement. In order to find how great an effect may be caused by such errors and by differences in machines and the method of operating them, the experiment was tried of sending a bar from six different acid open-hearth heats to six different testing laboratories. The pieces were rolled flats, 2″x⅜″, and each series was made up of one piece from each of the six bars, so that the only possible difference between the steel sent to the various places would be the difference between parts of the same bar.

All pieces were tested in the shape in which they left the rolls without any machining, and although the edges were not perfectly smooth, they were so nearly true that only one operator referred to any difficulty in making a true measurement. Table 105 exhibits the results reported. The bars were tested by The Central Iron and Steel Works, Harrisburg, Pa., The Baldwin Locomotive Works, Philadelphia, Pa., The Pottstown Iron Company, Pottstown, Pa., The Carnegie Steel Company, Pittsburg, Pa., The Carbon Steel Company, Pittsburg, Pa., and The Pennsylvania Steel Company, Steelton, Pa., but the identity of the different works is purposely concealed in the table under the letters *A*, *B*, *C*, etc., to avoid invidious comparisons.

An examination will show that there are quite important variations in every one of the factors. Moreover, the divergence is not the result of averaging erratic individuals, for whenever one average is higher than another, it is because the majority of the bars are higher when taken separately.

The variations in contraction of area may easily be explained, for the determination rests upon the most accurate measurements of an irregular broken body. In a bar having an original section of 2″x⅜″, the fractured end will have a thickness of about 0.20 inch, and almost invariably will be of irregular form, the sides being concave rather than flat. A true estimation of the broken area could be made only by the most careful duplicate readings and by the aid of the calculus.

These refinements are out of the question in practice, but the chances of error must always be considered when a test bar falls a little short of the requirements.

TABLE 105.

Physical Properties of the Same Bars of Steel, as Determined by Different Laboratories.

NOTE.—All bars were rolled flats, 2″x3/8″, and were not machined.

	Number of heat.	Tested by					
		A.	B.	C.	D.	E.	F.
Ultimate strength; pounds per square inch.	10027	58130	57880	58560	57710	57980	59230
	10028	60790	60140	61740	60080	60660	61830
	10030	63560	63330	64530	63180	63450	64280
	10065	60840	611[illegible]0	62180	60440	61290	62200
	10066	62840	62700	63480	61970	62630	64170
	10072	61160	62190	61730	61390	61640	62110
	Average,	61220	61233	62037	60795	61275	62303
Elastic limit; pounds per square inch.	10027	42400	37350	38900	37490	39020	39730
	10028	42200	37940	41400	38720	39730	41320
	10030	43620	40780	42540	38940	40740	42770
	10065	41540	38150	42250	38710	40210	41250
	10066	42610	40350	42110	38905	40180	43140
	10072	41400	37650	41770	38710	40950	39860
	Average,	42295	38703	41495	38579	40138	41345
	Elastic ratio,	69.1	63.2	66.9	63.5	65.5	66.4
Elongation in 8 inches; per cent.	10027	29.25	29.00	30.50	30.37	30.75	29.75
	10028	30.75	30.00	32.00	29.75	31.00	29.50
	10030	29.00	29.00	31.00	28.12	29.00	28.50
	10065	29.25	28.75	30.50	30.25	29.50	32.50
	10066	29.25	32.25	30.50	29.12	33.25	29.50
	10072	30.00	33.75	34.25	29.37	30.75	29.00
	Average,	29.58	30.46	31.46	29.50	30.71	29.79
Reduction of area; per cent.	10027	61.3	61.3	60.6	56.2	54.1	61.2
	10028	63.1	59.7	62.9	58.9	53.3	62.3
	10030	60.1	57.0	60.0	55.9	52.7	57.8
	10065	61.8	58.4	60.6	56.7	55.9	61.6
	10066	61.5	59.9	60.9	54.0	52.5	60.0
	10072	61.8	57.6	61.2	57.4	54.1	61.3
	Average,	61.6	59.0	61.0	56.5	53.8	60.7

The variations in elongation may be partially accounted for by unlike methods of measurement, for if the original punch-marks be put on the outer edge of the bar, they will give a different reading after fracture than if they were put in the center line, owing to the unequal distortion of the bar. This complication would not occur in the case of a round test-piece.

The differences in ultimate strength and elastic limit are due in some measure to slight variations in the original measurements of the bar. The elastic limit was found by

noting the "drop of the beam," this being the universal practice in American steel works and rolling mills. This method has been criticized by some investigators, who advocate an autographic device for registering the point where the elongation ceases to be exactly proportionate to the load. The introduction of such a system would result in endless confusion, since all specifications and contracts of the present day are based upon the elastic limit as now determined by the fall of the beam.

The statement that the current method is especially inaccurate is open to debate. In the series of tests given in Table 105, it will be found that the elongation, as determined by different observers, varies from 29.50 to 31.46 per cent., these figures being in the ratio of 100 to 106.6, or a range of error of 6.6 per cent. The reduction of area varies from 53.8 to 61.6 per cent., a ratio of 100 to 114.5, or a range of error of 14.5 per cent. The elastic ratio varies from 63.2 to 69.1 per cent., a ratio of 100 to 109.3, or a range of error of 9.3 per cent.

Thus the determination of the elastic ratio is much more accurate than the results on contraction of area, and nearly as accurate as the results on elongation, both of which are determined by exact measurements made on the piece when at rest. It would be quite in order for reformers to apply their energies to the accurate determination of the reduction of area and the elongation, instead of trying to substitute a new method for determining the elastic limit, especially when this method has been publicly branded as inaccurate.*

As a rule the autographic device gives a slightly lower reading than is found by the drop of the beam; thus in a paper by Gus. C. Henning† there are given the determinations of the elastic limit on a series of tests, as found by the two methods. I have averaged the list of heats where both readings are given, and find that in thirty-eight cases the autographic record was 46.6 per cent. of the ultimate strength, while the beam dropped at 52.9 per cent.; in the annealed bar the first method gave 51.6 per cent., and the second 56.9 per cent.

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* Lewis. *Trans. Am. Soc. Civil Eng.*, Vol. XXXIII, p. 351.
† *Trans. Am. Soc. Mech. Eng.*, Vol. XIII, p. 572.

Such a marked difference is not found in all cases, as shown by Table 106, which gives the results obtained by E. A. Custer, who at the time was connected with The Baldwin Locomotive Works, Philadelphia, Pa.

In the case of the slow speed there is less difference between the two determinations of the elastic limit than is shown by Henning, while with the fast speed there is more. This matter of the influence of the pulling speed upon the recorded physical properties is considered in the next section.

TABLE 106.

Parallel Determinations of the Elastic Limit by the Autographic Device and by the Drop of the Beam.*

No. of tests.	Pulling speed.	Ultimate strength; pounds per sq. in.	Elastic limit; pounds per square in. as determined by		Elastic ratio; per cent., as determined by	
			Auto-graphic device.	Fall of beam.	Auto-graphic device.	Fall of beam.
6	1 inch in 3 minutes.	56820	36120	37510	63.6	66.0
3	4 inches in 1 minute.	58870	35890	40530	61.0	68.8

The whole subject of the determination of the elastic limit was discussed in *The Engineering News*, of July 25, 1895. After reviewing at great length the arguments presented by several engineers in previous issues, and after quoting from many authorities, the following conclusions were reached:

"Having thus shown the impossibility of determining by micrometric measurement the elastic limit, when it is defined as the point at which the rate of stretch begins to change, and the extreme variability of the position of the so-called 'yield point' with the method of running the machine and with the method of measuring and recording results, had we not better drop these new definitions and methods of attempting to locate points whose position is so extremely variable, and whose determination depends so largely upon the personal equation of the observer, and return to the good, old-fashioned definitions and methods? If for scientific purposes there is any need for determining microscopically that point at which the rate of stretch begins microscopically to change, let us call that point the 'limit of proportionality,' as Bauschinger did, and leave its determination to the college professors.

* From E. A. Custer, Baldwin Locomotive Works, Philadelphia, Pa.

"Let us keep the old term elastic limit with its old significance as that point at which a permanent set visible to the naked eye takes place, at which the rate of stretch increases so that the increase may be (albeit with some difficulty) distinguishable by the use of a pair of dividers and a magnifying glass, or more easily and certainly by the drop of the beam, or by the increase in the number of turns of the crank needed to produce a given increase in stretch.

"For the purpose of determining this elastic limit let the testing machine be run by hand until the limit is passed and the record taken (or run by hand between the load of 30000 pounds and the elastic limit), and then let the power gear be thrown in and the test completed in the present rapid fashion. Since the term 'yield point' is quite recent, and it has no meaning essentially different from the words 'elastic limit' in time-honored practice, why need it be used at all?"

These conclusions represent common sense in their summary dealing with the petty theories of enthusiasts, who are so wrapped up in the accurate determination of a micrometrical measurement that they ignore the more important variations inherent in the method itself, not to mention the still more overwhelming differences caused by changes in the history and shape of the material. I do not see, however, why it is necessary to revert to the primitive and laborious method of driving a machine by hand when there is a power attachment with different pulleys. The speed should be lower during the determination of the elastic limit than can be used for breaking the piece, but a specification that this work must be done by hand is a confession of lack of ingenuity which is not creditable to engineering science, and which is not justified by facts.

SEC. 142.—*Effect of variations in the pulling speed of the testing machine upon the recorded physical properties.*—To find the effect of variations in pulling speed, ten different rivet rods were taken from an acid open-hearth heat. From each rod five bars were cut, and each one of these was broken at a different speed. The results are given in Table 107.

It will be seen that a decrease in pulling speed is accompanied by a decrease in the ultimate strength, elastic limit,

elastic ratio, and elongation. The differences are not extreme, but their regularity, when viewed in connection with the uniform conditions of the experiment and the evident homogeneity of the material, makes the testimony almost conclusive. In the case of the slowest speed there is an exception to this rule in a marked increase of extension, and an

TABLE 107.

Effect of Variations in the Pulling Speed of Testing Machine upon the Recorded Results.

NOTE.—Tests were made by The Pennsylvania Steel Company.

	Number of bars.	Pulling speed; inches per minute.				
		4.50	3.00	0.67	0.38	0.07
Ultimate strength; pounds per square inch.	1	61060	61360	60640	60240	59660
	2	61140	60760	59200	59440	59100
	3	61610	61230	59910	59680	59100
	4	61500	61150	58950	59620	59220
	5	61870	61580	59960	59910	59760
	6	60200	59720	59040	58240	59100
	7	60620	60140	59290	59380	58200
	8	60520	59580	58760	58400	58160
	9	61200	61100	60000	59620	58870
	10	61030	60100	59480	59340	59100
	Av.	61075	60672	59523	59387	59027
Elastic limit; pounds per square inch.	1	46640	44930	43240	42650	39610
	2	44070	43500	44810	41980	39480
	3	46920	44680	42220	41270	39250
	4	46730	45560	42720	41830	40300
	5	45080	46300	43120	43430	40480
	6	44360	43400	41690	40810	39240
	7	47500	43670	43090	41830	38950
	8	44680	44680	42650	41370	39720
	9	45000	43440	42380	40860	39720
	10	46100	43940	43120	41600	39720
	Av.	45708	44410	42904	41763	39647
Elastic ratio; per ct.	Av.	74.84	73.20	72.08	70.32	67.17
Elongation in 8 inches; per cent.	1	29.50	28.25	31.00	28.00	34.00
	2	32.00	30.50	30.75	29.50	31.25
	3	31.75	32.00	27.50	29.25	31.25
	4	27.75	27.00	28.50	28.00	32.25
	5	31.50	30.50	30.00	29.50	30.25
	6	30.50	30.75	29.00	30.00	32.00
	7	29.50	30.50	31.00	31.00	32.75
	8	31.00	28.50	29.25	28.00	32.75
	9	30.00	32.00	28.00	30.00	30.75
	10	29.65	31.75	29.50	30.00	32.00
	Av.	30.32	30.18	29.45	29.33	31.93
Reduction of area; per cent.	1	66.1	65.9	66.7	67.0	68.4
	2	67.1	66.0	66.0	66.7	67.1
	3	62.3	62.4	63.9	63.2	63.4
	4	64.9	65.0	64.9	65.9	67.7
	5	63.3	64.4	64.2	63.7	65.0
	6	66.0	66.2	66.7	67.3	66.0
	7	66.8	66.3	67.4	67.1	67.9
	8	62.4	62.6	68.0	63.1	64.8
	9	64.5	63.5	64.3	65.8	66.9
	10	66.2	66.0	66.1	67.1	67.6
	Av.	64.96	61.83	65.82	65.69	66.48

inspection will show that this does not arise from an average of erratic members, but from an increase in every bar. This point is not of great practical importance, since it requires nearly an hour to break a single bar of ductile steel at this speed. The reduction of area seems to remain practically constant throughout the series.

The natural result of this investigation would be a tendency toward higher breaking speeds. It is believed, however, that this may be carried too far, since with fast work it is more difficult to take accurate readings.

CHAPTER XVII.

THE INFLUENCE OF CERTAIN ELEMENTS ON THE PHYSICAL PROPERTIES OF STEEL.

SECTION 143.—*Difficulties attending the quantitative valuation of alloyed elements.*—Numerous investigations have been conducted to discover the influence of different elements on the strength and ductility of steel, a common method being to melt definite combinations in crucibles and ascribe the physical result to the known variables, under the assumption that all other things are equal. This system of experiment will answer in noting the effect of large proportions of certain elements, or in showing the qualitative influence of unusual ingredients; but it is worthless in the accurate quantitative valuation of minute proportions of the metalloids, since small variations in the chemical equation are masked by irregularities in the detail of casting and working. The problem is also complicated by numberless combinations of different percentages of the various elements, so that it is difficult to obtain groups of charges where there is only one variable.

It has, therefore, not infrequently happened that inconclusive data have been joined to bad logic, and the conclusions of special investigators have been at variance with all the teachings of experience. It is not my purpose to enumerate all the theories or deductions of experimenters, but I shall aim to give a general survey of the situation. In Part I each element is considered separately, and the views therein advanced are in accord with the general consensus of opinion among metallurgists. Parts II and III give the result of special investigations into the effect of carbon, silicon, manganese, phosphorus, and sulphur upon the tensile strength of steel, and a determination of the strength of pure iron.

Part I.

EFFECT OF CERTAIN ELEMENTS AS DETERMINED BY GENERAL EXPERIENCE AND BY THE USUAL METHODS OF INVESTIGATION.

Sec. 144.—*Influence of carbon.*—The ordinary steel of commerce is carbon-steel; in other words, the distinctive features of two different grades are due for the most part to variations in carbon rather than to differences in other elements. There are often wide variations in manganese, phosphorus, silicon, etc., but it is rarely that the carbon content does not determine the class in which the material belongs. This selection of carbon as the one important variable arose primarily from the fact that primitive Tubal Cains could produce a hard cutting instrument with no apparatus save a wrought-iron bar and a pile of charcoal; and the natural developments in manufacture have led to the conclusion that a given content of carbon will confer greater hardness and strength, with less accompanying brittleness, than any other element.

There are certain exceptions to be taken to this statement in the case of hard steels made by manganese, chromium, or tungsten, but it may be accepted as true in soft steel. It follows, therefore, that no limit should ever be placed to the carbon allowed in any structural material if a given tensile strength is specified. It is, of course, true that every increment of carbon increases the hardness, the brittleness under shock, and the susceptibility to crack under sudden cooling and heating, while it reduces the elongation and reduction of area, but the strength must be bought at a certain cost, and this cost is less in the case of carbon than with any other element.

It is not my purpose to discuss the various ways in which carbon manifests itself under different conditions of work and temperature, for, notwithstanding the learned and laborious investigations of Howe, Osmond, Hadfield, Ledebur, and others, there is a wide difference of opinion on cardinal points, and such abstruse theories regarding the molecular equation, that all save the studious metallurgist may wait for the doctors to agree.

In structural steels, low in carbon, which have not been tempered or annealed, it may be assumed that all the carbon is

combined with the iron, and is in the same molecular condition in all bars. Manipulations by heating and cooling can alter this condition, the extent and nature of such changes being determined both by the temperature to which the metal is heated and the rate at which it is cooled. The chemical determinations are generally made by the color method, which does very well in current steel-works practice for rough comparison, when all bars have been heated and cooled in the same manner and the carbon is in the same molecular condition, but it is far from reliable, and in all disputed cases there must be an analysis by combustion.

SEC. 145.—*Influence of silicon.*—The contradictory testimony concerning the effect of silicon on steel has been well summarized by Mr. Howe,* who records many examples of exceptional steels with abnormal contents of silicon, and who fully discusses the theories advanced by different writers. He finds no proof that silicon has any bad effect upon the ductility or toughness of steel, and he concludes that the bad quality of certain specimens is not necessarily due to the silicon content, but to other unknown conditions. A Bessemer steel with high silicon is sometimes produced by hot blowing, but it will be entirely wrong to compare such metal with the common product and ascribe all differences to the chemical formula, rather than to the circumstances which created that formula.

Since the appearance of The Metallurgy, an able paper has been written by Hadfield,† who produced alloys with different contents of silicon by melting wrought-iron and ferro-silicon in crucibles. The metal was cast in ingots 2½ inches square, and these were reduced by forging to 1¾ inches square and then rolled into bars 1⅛ inches in diameter. In the list of analyses in the paper referred to, there are slight differences in the composition of drillings from different bars of the same ingot, but in Table 108 I have averaged the results of each cast so as to show the nature of the material under investigation, and have given the physical results on the rolled bars in their natural state.

Bars *A*, *B*, *C*, and *D* showed a silky fracture after breaking,

* *The Metallurgy of Steel*, p. 36.

† *On Alloys of Iron and Silicon. Journal I. and S. I.*, Vol. II, 1889, p. 222.

but with higher silicon the crystallization was very coarse. They also showed no great hardening or brittleness after being quenched in water from a yellow heat, while even the higher alloys, although made quite stiff by the chilling, were not rendered very hard, and preserved a good degree of ductility. With the exception of *A* the ingots forged well even up to 5.5 per cent. of silicon, but all attempts at welding were unsatisfactory.

TABLE 108.

Physical Properties of Silicon Steels.*

Mark.	Carbon; per cent.	Silicon; per cent.	Manganese; per cent.	Sulphur; per cent.	Phosphorus; per cent.	Ultimate strength; pounds per square inch.	Elastic limit; pounds per square inch.	Elastic ratio; per cent.	Elongation in 2 inches; per cent.	Reduction of area; per cent.	Ultimate strength after annealing; pounds per square inch.
A	.14	.21	.14	.08	.05	73920	49280	66.7	30.05	54.54	56000
B	.18	.77	.21	. . .	. .	76160	56000	73.5	29.50	54.54	64960
C	.19	1.57	.28	. . .	. .	84000	62720	74.7	31.10	50.58	73920
D	.20	2.14	.25	.06	.04	88480	69440	78.5	18.48	28.02	76160
E	.20	2.67	.25	. . .	. .	95200	71680	75.3	17.60	24.36	71680
F	.21	3.40	.29	. . .	. .	106400	78400	73.7	11.10	14.22	87360
G	.25	4.30	.36	. . .	. .	109760	100800	91.8	0.004	0.20	85120
H	.26	5.08	.29	.06	.04	107520	not visible	. . .	0.30	0.70	56000

These results are of the highest value in showing that silicon can not be classed among the highly injurious elements, for in similar proportion phosphorus and sulphur would be out of the question, manganese would give a worthless metal, and carbon would change the bar to pig-iron. It will, therefore, be only reasonable to suppose that small quantities can not exert a very deleterious influence.

The only bar in the table which contains a moderate content of silicon is *A* with .21 per cent., and it is recorded that this ingot did not forge well and did not weld, but it must be considered that the manganese was only .14 per cent. while the sulphur was .08 per cent. and the phosphorus .05 per cent. Assuredly, it would hardly be expected that such metal would forge very well, and it is not singular that it gave trouble, while other experimenters have forged and welded steel with similar contents of silicon when the associated elements were in proper proportion.

* Condensed from Hadfield. *Journal I. and S. I.*, Vol. II, 1889, p. 222.

In the whole series it must be considered that the amount of work done upon the ingot in reducing it from 2½ inches square to 1⅛ inches in diameter was wholly insufficient to give a proper structure, so that little weight can be attached to the determination on any one bar. This renders it difficult to calculate the exact effect of silicon, especially since the bars *A* and *B* present some contradictions. Thus *B* contains .04 per cent. more carbon than *A*, .07 per cent. more manganese, and .56 per cent. more silicon, and yet has only 2240 pounds more tensile strength per square inch.

TABLE 109.

Influence of Silicon on the Tensile Strength as Shown by Table 108.

Mark.	Carbon; per cent.	Silicon; per cent.	Manganese; per cent.	Ultimate strength; pounds per square inch.	Difference in strength between each test and the bar B.	Difference in strength due to difference in carbon.	Difference bet. the last two columns showing increase in strength due to silicon.	Increase in percentage of silicon compared with bar B.	Increase in strength due to .01 per cent. of silicon.
B	.18	.77	.21	76160	. . . . .	. . . . .	. . . . .	. . . .	. . .
C	.19	1.57	.28	84000	7840	1210	6630	.80	83
D	.20	2.14	.25	88480	12320	2420	9900	1.37	72
E	.20	2.67	.25	95200	19040	2420	16620	1.90	87
F	.21	3.40	.29	106400	30240	3630	26610	2.63	101
G	.25	4.30	.36	109760	33600	8470	25130	3.53	71
H	.26	5.08	.29	107520	31360	9680	21680	4.31	50

Inspection shows that *A* is probably the erratic member, for its strength is altogether too high for its composition. Moreover, the annealed bars show a loss in strength of 24 per cent. from the natural in *A*, while bars *B*, *C*, and *D* give 15, 12, and 14 per cent., respectively, so that it is likely that *A* is finished at too low a temperature and has a higher strength than really belongs to it. For this reason it will be set aside as abnormal, and in Table 109 the bar *B* is taken as a basis to investigate the differences in tensile strength. No allowance is made for manganese, since this element is fairly constant in all the specimens, but a value of 1210 pounds per square inch is given to carbon in accordance with the formula given in Table 128. After this allowance the remaining variations are ascribed to silicon, but this is not strictly correct as no data are at hand concerning the content of phosphorus, so that the answer is open to question.

This table can not be called a conclusive equation of the effect of silicon, for the carbon was determined by color instead of combustion, the number of tests is altogether too limited, and no account is taken of phosphorus, but there seems to be a strengthening effect of about 80 pounds for every .01 per cent. of silicon up to a content of four per cent., while beyond this there is a deterioration of the metal, as shown in Table 108. This would mean an increase of only 1600 pounds for .20 per cent. silicon, being one-third more than that produced by .01 per cent. of carbon. (See Table 128.) It has already been noted that *A*, which was the only bar containing an ordinary percentage of silicon, gave abnormal results in tensile strength, but this can not be due to silicon, for the elastic ratio is quite normal, the elongation fair, and the reduction of area very good.

TABLE 110.

Physical Properties of Steels Containing from .01 to .50 Per Cent. Silicon.*

NOTE.—All bars rolled well; they bent well both hot and cold except No. 11, which broke cold at an angle of 50°; they all welded perfectly; the differences in hardness were scarcely perceptible.

Number of test.	Silicon; per cent.	Carbon; per cent.	Sulphur; per cent.	Phosphorus; per cent.	Manganese; per cent.	Elastic limit; pounds per square inch.	Ultimate strength; pounds per square inch.	Elastic ratio; per cent.	Elongation in 10 inches; per cent.	Reduction of area; per cent.
1	.010	.16	.050	.060	.550	49280	66394	74.3	23.1	48.8
2	.061	.16	.028	.058	.619	49750	70806	70.3	20.4	40.7
3	.070	.15	.084	.051	.500	47152	66102	71.3	22.9	51.5
4	.092	.21	.084	.064	.634	50243	75398	66.6	19.4	44.1
5	.102	.18	.028	.066	.662	47622	75197	63.4	20.6	51.4
6	.121	.19	.064	.068	.576	50848	71367	71.2	21.9	43.7
7	.315	.13	.028	.057	.480	47690	65901	72.4	24.8	56.6
8	.247	.19	.028	.074	.642	49795	77728	64.0	17.6	49.6
9	.320	.15	.040	.081	.490	49997	74435	67.1	16.7	36.1
10	.382	.16	.042	.087	.533	55373	79901	69.3	18.0	30.7
11	.504	.18	.094	.121	.455	59024	82253	71.7	19.4	34.8

An investigation into the effect of ordinary proportions of silicon was conducted by Turner under the auspices of the British Association. Table 110 gives the results as published in *Journal I. and S. I.*, Vol. II, 1888, p. 302. There are considerable variations in the elements other than silicon, and the bad character of No. 11 may well be explained by its

* Report of British Association, 1888.

high content of phosphorus. For better comparison Table 111 gives the averages of the first four tests, all of which are below .10 per cent. in silicon, and the last three, which are above .30 per cent.

TABLE 111.

Comparative Physical Properties of Low-Silicon and High-Silicon Steels; from Data in Table 110.

Group.	Number of heats in group.	Composition; per cent.					Elastic limit; pounds per square inch.	Ultimate strength; pounds per square inch.	Elastic ratio; per cent.	Elongation in 10 inches; per cent.	Reduction of area; per cent.
		Si.	C.	S.	P.	Mn.					
1	4	.056	.170	.061	.058	.576	49106	69675	70.5	21.5	46.3
2	3	.402	.160	.059	.096	.493	54798	78863	69.5	18.0	33.9

The effect of the difference caused by elements other than silicon may be calculated from the formula given in Table 128, carbon being taken at + 121 pounds for .001 per cent., and phosphorus at + 89. The result is as follows:

	Lbs. per sq. in.
Group II should be stronger than Group I.	
On account of phosphorus, 38 × 89	3382
Group II should be weaker than Group I.	
On account of carbon, 10 × 121	1210
Net strengthening from constituents other than silicon	2172
Strengthening from all constituents including silicon	9188
Strengthening due to .35 per cent. of silicon	7016
Strengthening due to each .01 per cent. of silicon	200

This signifies that .20 per cent. of silicon would give an increase in ultimate strength of 4000 pounds per square inch, which is only a little more than would be given by .03 per cent. of carbon. (See Table 128.)

The influence of silicon upon the tensile strength is often confounded with that of carbon. It is well known that the addition of high-silicon pig-iron to a charge of low steel strengthens the metal more than a similar addition of ordinary pig-iron. But the fact is lost sight of that this silicon prevents the burning of carbon, both by the absorption of oxygen and by the deadening of the bath, so that the resultant metal is of higher carbon.

If the ordinary color method were reliable, this would be detected and proper credit given to it, but it often happens that an increment of .03 per cent. of carbon is not shown by analysis, so that its effect upon the ultimate strength, which will amount to about 3500 pounds per square inch, will be incorrectly ascribed to whatever small percentage of silicon has survived the reactions during recarburization. This criticism on the determination of carbon applies to the data given in Tables 108 and 110, and renders the calculations thereon of limited value.

These conclusions are corroborated by the testimony of Groups 49, 52, 54, 55, 56, 57, 60, and 61 in Table 121, as shown in Figure XVIII. All of these groups contain high silicon, but they do not seem to differ materially from the normal steels. Between the limits of 82000 and 100,000 pounds ultimate strength there are seven groups in Table 121, Nos. 48, 49, 50, 51, 52, 53, and 54, some containing high silicon and some with a low percentage, but the great variations do not seem to have any decided effect in altering the trend of the curve, although the contents of sulphur, phosphorus, and manganese are fairly constant. (This question is discussed more fully in Section 158.)

It is well known that many continental works have habitually made their rails with from .30 to .60 per cent. of silicon, and that all requirements of strength and ductility have been met. All the authorities do not approve this practice, and it is stated by Ehrenwerth,* that the latest results are rather in the opposite direction in the case of low steels,† but I was told some years ago, by the manager of one of the French establishments, that the only way in which he was able to fill one contract with particularly severe specifications, was by making the rails contain from .30 to .40 per cent. of silicon, since a less proportion would not stand the drop-tests. It is not necessary to question whether this conclusion was warranted or not; it is enough to know that the steel was of the best quality, whether on account of the silicon or in spite of it.

The fact that silicon may be allowed in rails has been

* *Das Berg- und Hüttenwesen auf der Weltausstellung in Chicago*, 1895.

† See page 78, *ante*.

acknowledged by Sandberg, who writes as follows:* "Silicon up to .30 per cent., with carbon .30 to .40 per cent., does not harden steel or make it brittle, and *diminishes its strength in such small degree* as not to imperil the safety of the rail." The italics in the quotation are my own, and are to call attention to the implication that silicon lowers the strength rather than raises it.

Exceptional cases have been recorded of soft steels with high silicon, like the very tough rail mentioned by Snelus,† with carbon below .10 per cent. and silicon .83 per cent. It must be considered, however, that although this might have been very tough for a rail, it does not follow that it was very tough for soft steel, but it is quite certain that it could not have been bad or brittle.

With the knowledge possessed concerning the relative effect of impurities upon hard and soft steels, the assumption would almost be justified that low-carbon metal might be allowed to contain a larger percentage of silicon than higher steel. There is no need, however, of such an admission, for structural steels do not often contain over .05 per cent. of silicon, while usually they hold less than .03 per cent.

Tool steel is subjected to the most severe of all tests in the exposure of a hardened edge to the blows of a hammer or the shocks of a planer. It was not the laboratory but the requirements of general practice from which was unconsciously evolved the formula for such metal, requiring low phosphorus, low sulphur, and low manganese. In this process of natural selection no mention was made of silicon. It is true that some makers try to keep it as low as possible, but a large part of the best steel has regularly contained, year after year from .20 to .80 per cent. of this element.

Notwithstanding all this testimony as to the harmlessness of silicon, it is firmly believed by many practical metallurgists that the presence of even .03 per cent. materially injures the quality of soft steel, such as is used for fire-boxes. I can not positively assert the contrary, but I believe that the effects ascribed to silicon may be due to the conditions of

* *Proc. English Inst. Mech. Eng.*, 1890, p. 301.

† *On the Chemical Composition and Testing of Steel Rails. Journal I. and S. I.*, Vol. II, 1882, p. 583.

manufacture which gave rise to it, or to the conditions of casting which it produces. These conditions might be fatal under one practice, as, for instance, when ingots are rolled directly into plates, while they might be harmless, or even beneficent, when an ingot is roughed down and reheated. The opinions of practical men are sometimes of more value than the learned conclusions of theorists, and must never be ignored, but they are not always inerrant.

SEC. 146.—*Influence of manganese.*—Spiegel-iron or ferromanganese is added to a heat of steel at the time of tapping in order that it may seize the oxygen, which is dissolved in the bath, and transfer it to the slag as oxide of manganese; but this reaction is not perfect, as shown in Section 77, and there is reason to believe that all common steels contain a certain percentage of oxygen.* Steel low in phosphorus and sulphur requires less manganese than impure metal, although it is difficult to see why there should be less oxygen to counteract, and this indicates that the function of the manganese is to prevent the coarse crystallization which the impurities would otherwise induce.

Besides conferring the quality of hot ductility, manganese also raises the critical temperature to which it is safe to heat the steel, for just as it resists the separation of the crystals in cooling from a liquid, so it opposes their formation when a high thermal altitude augments the molecular mobility. These two manifestations of the same general force render manganese one of the most valuable and essential factors in the making of steel, although there is no doubt that it has been used too freely in some cases.

Years ago some of the railmakers of the country looked upon it as a panacea for all bad practices in the Bessemer and the rolling mill, and steel often contained from 1.25 to 2.00 per cent. of manganese, but it was soon discovered that such rails were brittle under shock, so that the permissible maximum has been gradually lowered, and the standard product of the present day contains from .70 to 1.00 per cent. In higher steels the same lesson has been learned, but in this case the necessity of a low content is far more marked, since a percentage which is perfectly harmless in unhardened steel will

* See Section 153 for a further discussion on this point.

cause cracking if the metal be quenched in water. For this reason it is advisable to reduce the proportion of this element in hard steel to the lowest possible point.

In structural metal there is no quenching to be done and the line of maximum manganese need not be drawn too low. It is much more convenient for manufacturers to produce a higher tensile strength by the use of spiegel-iron, which contains manganese, than with ordinary pig-iron, since the presence of manganese deadens the metal and prevents the oxidation of the carbon.

Thus it happens that an increased tensile strength resulting from the addition of more recarburizer is usually accompanied by an increase in the content of manganese, and it is currently assumed that a considerable part of the extra strength is due to the higher percentage of this element. In great measure this is an error, for the increase in carbon is often sufficient to account for the change.

Ferro-manganese containing 80 per cent. of manganese holds about 5 per cent. of carbon, and since about one-third of the manganese is lost during the reaction while very little carbon is burned, it follows that about $\frac{2}{3} \times 80 = 53$ points of manganese will be added to the steel for every 5 points of carbon. Thus, if the content of manganese in any heat be raised .20 per cent. by an increase in the amount of the recarburizer, there will at the same time be an increment of .02 per cent. of carbon.

This slight change in carbon will not always be detected by the color method, particularly as an increase in manganese interferes with the accuracy of the comparison by altering the tint of the solution, and so the effect of this carbon, representing an increase in tensile strength of about 2400 pounds per square inch, is often ascribed to the increment of manganese. It is necessary, therefore, to carefully compare steels where the composition is thoroughly known to find the effect of this element, and this is done in Parts II and III of this chapter.

It is also currently believed that manganese reduces the ductility of steel to a great extent, but Table 112 will show that the effect is not well marked. This table is made by grouping together heats of the same general character and

of about the same tensile strength, and separating them into two classes according to their manganese content. No arbitrary line is drawn between a high and a low percentage, but each group is divided so that the number is as nearly equal as possible on each side. An unequal number is due solely to the fact that several heats may have exactly the same content, and these must all be placed either on one or the other side of the line.

TABLE 112.

Comparative Physical Properties of Open-Hearth Steel with Different Contents of Manganese.

Made by The Pennsylvania Steel Company.

Group.	Kind of steel.	Limits of ultimate strength in group; pounds per square inch.	Phosphorus; per cent.	Relative manganese.	Number of heats.	Manganese; per cent.	Ultimate strength; pounds per square inch.	Elastic limit; pounds per square inch.	Elongation in 8 inches; per cent.	Reduction of area; per cent.	Elastic ratio; per cent.	Shape of test; in inches.
I	Acid	55000 to 60000	.08	Low High	7 6	.30 .37	57922 58881	38692 38598	29.91 28.08	59.02 57.07	66.8 65.6	¾ diam.
II	Basic	55000 to 63000	.03	Low High	11 11	.44 .57	58005 59563	38547 40133	30.16 30.36	60.21 58.55	66.5 67.4	2x⅜
III	Acid	60000 to 65000	.08	Low High	16 14	.35 .51	62180 62605	41308 41169	28.00 27.65	50.89 54.66	66.4 65.8	¾ diam.
IV	Acid	65000 to 70000	.08	Low High	26 32	.51 .78	67421 68192	43923 45854	25.96 25.82	51.29 51.50	65.1 67.2	¾ diam.
V	Acid	70000 to 75000	.08	Low High	18 25	.60 .91	72353 72115	46836 48359	24.23 24.63	47.79 47.73	64.7 67.1	¾ diam.
VI	Acid	75000 to 80000	.08	Low High	11 11	.65 .84	77520 78083	49411 50226	22.34 23.63	44.42 48.49	63.7 64.3	¾ diam.
VII	Acid	80000 to 85000	.08	Low High	9 9	.68 .82	81747 81860	51219 52231	20.63 22.67	41.04 47.75	62.7 63.8	¾ diam.
VIII	Acid	85000 to 90000	.08	Low High	5 5	.75 .83	86460 88034	54517 55409	20.41 20.66	40.56 41.92	63.1 62.9	¾ diam.

It will be evident that there is no marked difference between the steels of high and low manganese, and the results of the eight different groups are so uniform in their testimony that the work of chance must be almost absent. These records of ductility, however, do not take into account the very important quality of resistance to shock. It has always been a problem to devise some way of applying a satisfactory test in this direction, but the method is yet to be found. A few crude

experiments which I performed on steel of high manganese, to see how it would act under shock, are given in Table 113.

TABLE 113.

Resistance to Shock of Steel Containing about 1.00 Per Cent. of Manganese.

All tests ¾-inch rolled rounds, made by The Pennsylvania Steel Company.

Heat number.	Manganese; per cent.	Conditions under which test was made.	Ultimate strength; pounds per square inch.	Elastic limit; pounds per square inch.	Elongation in 8 inches; per cent.	Reduction of area; per cent.
6960	1.00	Average of two tests, pulled quietly	71040	47055	25.87	55.05
		Average of two, hammered from start to finish	70770	46380	26.12	61.40
6961	1.03	Average of two tests, pulled quietly	72175	48075	27.00	54.98
		Average of two, hammered from start to finish	71120	47330	26.00	59.20
6962	0.94	Average of two tests, pulled quietly	74020	48165	25.62	52.60
		Average of two, hammered from start to finish	74490	48340	23.50	55.70
6963	1.13	One bar, pulled quietly	81070	52880	22.50	43.60
		One bar, hammered from elastic limit to fracture	80460	52760	23.50	48.30
		One bar, hammered from failure to fracture,	78050	51800	19.25	55.30
		One bar, began hammering at 72000 pounds, and moved scale weight back as the bar weakened	69040	52760	21.00	47.80
6981	0.82	One bar, pulled quietly	67340	46030	28.12	55.00
		One bar, hammered from failure to fracture,	65940	44430	28.00	57.90
6982	0.91	One bar, pulled quietly	66700	46310	26.00	55.93
		One bar, hammered from failure to fracture,	67240	46090	31.25	55.60
6983	1.03	One bar, pulled quietly	69700	47650	26.00	51.70
		One bar, hammered from failure to fracture,	70080	46360	27.12	53.70

The bar was struck while in tension with a copper hammer, each blow being powerful enough to have permanently bent the bar if it had not been continually straightened by the action of the machine. One of the effects of this hammering is to momentarily loosen the bar in the grips and make a sudden jar upon the piece. This action, coupled with the stress upon the outside fibres and the direct vibration, make the test quite exhaustive, although from the difficulty of measuring the force of impact it can hardly be called practical. Some of the bars were not struck until "failure," or until the maximum stress had been reached. This was on account of the trouble from slipping or jumping above noted which followed the hammer-

ing at earlier periods, and it was taken for granted that if a bar would break at all from shock, the fracture would be likely to occur about the time when the piece was under destructive tension.

It will be evident that the hammering did not in any case determine the time of breakage, for each piece gave as good an elongation and reduction of area as a part of the same rod which was pulled in the usual manner.

It is not the intention to advocate the use of such a high content of manganese as is shown in Table 113. The general conclusion of metallurgists, evolved from experience, seems to point to as low a proportion as will ensure good working in the rolls. In the case of such ingots as are rolled directly into plates, the allowable content is limited by the requirement that the steel shall boil in the molds, but it does not follow because bad results accompany higher manganese in such practice, that the quality of the product is proportionally deteriorated when the ingot is roughed down and reheated.

The effect of large proportions of manganese upon steel is one of the most curious phenomena in metallurgy. As the content rises over 1.5 or 2.0 per cent. the metal becomes brittle and almost worthless, and further additions do not better the matter until an alloy is reached with about 6 or 7 per cent. manganese. From this point the metal is not only extremely hard, but possesses the rather peculiar property of becoming very much tougher after quenching in water, without any great change in hardness.

The physical properties of various manganese alloys is shown in Table 114, which is taken from an article by Hadfield,* who has made use of these valuable qualities in the making of car wheels, dredger links and pins, and other articles where the maximum of hardness must be combined with toughness. The great disadvantage of "manganese steel" is the impracticability of doing machine work upon it, for the best of hardened tools will crumble and wear out in contact with this metal. The usual method is to forge the piece accurately to size, while in the case of wheels a soft bushing is cast in the center and this may be bored to receive the axle.

* See also *The Mineral Industry*, Vol. IV, for an essay on Alloys of Iron by R. A. Hadfield.

SEC. 147.—*Influence of sulphur.*—Nothing is better established than the fact that sulphur injures the rolling qualities of steel, causing it to crack and tear, and lessening its capacity to weld. This tendency can be overcome in some measure by the use of manganese and by care in heating, but this does not in the least disprove that the sulphur is at work, but simply shows that it is overpowered. The critical content at which the metal ceases to be malleable and weldable varies with every steel. It is lower with each associated increment of copper, it is higher with each unit of manganese, and it is lower in steel which has been cast too hot.

TABLE 114.

Physical Properties of Forged Steel Containing from .83 to 21.69 Per Cent. Manganese.*

No. of sample.	Composition; per cent.			Natural.		Quenched in water.		Annealed.	
	Carbon.	Silicon.	Manganese.	Ultimate strength; pounds per square inch.	Elongation in 8 inches; per cent.	Ultimate strength; pounds per square inch.	Elongation in 8 inches; per cent.	Ultimate strength; pounds per square inch.	Elongation in 8 inches; per cent.
1	.20	.03	.83	73920	31	. . . . . .	. . . .	. . . . . .	. . . .
2	.40	.15	2.30	125440	6	. . . . . .	. . . .	. . . . . .	. . . .
3	.40	.09	3.89	85120	1	. . . . . .	. . . .	. . . . . .	. . . .
4	.52	.37	6.95	56000	2	51520	2	47040	2
5	.47	.44	7.22	60480	2	56000	2	60480	5
6	.61	.30	9.37	73920	5	87360	15	85120	16
7	.85	.28	10.60	76160	4	89600	17	91840	17
8	1.10	.16	12.60	87360	2	120960	27	82880	11
9	.92	.42	12.81	87360	5	136640	37	107520	20
10	.85	.28	14.01	80640	2	150080	44	107520	14
11	1.10	.32	14.48	87360	1	141120	37	109760	5
12	1.24	.16	15.06	109760	2	136640	31	105280	2
13	1.54	.16	18.40	114240	1	118720	10	87360	1
14	1.83	.26	18.55	96320	1	123200	5	. . . . . .	. . . .
15	1.60	.26	19.10	116480	1	132160	4	91840	1

In the making of common steel for simple shapes, a content of .10 per cent. is possible, and may even be exceeded if great care be taken in the heating, but for rails and other shapes having thin flanges it is advantageous to have less than .08 per cent., while every decrease below this point is seen in a reduced number of defective bars. It is impossible to pick out two steels with different contents of sulphur and say that the influence of a certain minute quantity can be detected, but it is none the less true that the effect of an increase or decrease of

*Condensed from Hadfield, *Journal I. and S. I.*, Vol. II, 1888, p. 70.

.01 per cent. will show itself in the long run, while each .03 per cent. will write its history so that he who runs may read.

The effect of sulphur upon the cold properties of steel has not been accurately determined, but it is quite certain that it is unimportant. In common practice the content varies from .02 to .10 per cent., and within these limits it seems to have no appreciable influence upon the elastic ratio, the elongation, or the reduction of area. It is more difficult to say that it does not alter the tensile strength, for a change of one thousand pounds per square inch can be caused by so many things that it is a bold venture to ascribe it to one variable. Webster* has stated that sulphur probably increases the ultimate strength at the rate of 500 pounds per square inch for every .01 per cent. I am inclined to think his conclusion is not founded on sufficient premises, and shall try to prove this in Sections 161 and 163.

In rivets, eyebars, and fire-box steel, the presence of sulphur is objectionable, for it will tend to create a coarse crystallization when the metal is heated to a high temperature, and reduce the strength and toughness of the steel. In other forms of structural material the effect of this element is probably of little importance.

SEC. 148.—*Influence of phosphorus.*—Of all the elements that are commonly found in steel, phosphorus stands preëminent as the most undesirable. It is objectionable in the rolling mill, for it tends to produce coarse crystallization and hence lowers the temperature to which it is safe to heat the steel, and for this reason phosphoritic metal should be finished at a lower temperature than pure steel in order to prevent the formation of a crystalline structure during the cooling. Aside from these considerations its influence is not felt in a marked degree in the rolling mill, for it has no disastrous effect upon the toughness of red-hot metal when the content does not exceed .15 per cent.

The action of phosphorus upon the finished material may not be dismissed in so few words. Mr. Howe† has gathered together the observation of different investigators, and the

* *Further Observations on the Relations between the Chemical Constitution and Physical Character of Steel. Trans. A. I. M. E.*, Vol. XXIII, p. 113.

† *The Metallurgy of Steel*, p. 67, *et seq.*

evidence seems to prove that the tensile strength is increased by each increment of phosphorus up to a content of .12 per cent., but that beyond this point the metal is weakened. Whether this last observation be correct or not is of little practical importance, for it would be criminal to use a metal for structural purposes that contained as much as an average of .12 per cent. phosphorus.

Below this point it is absolutely certain that phosphorus strengthens low steels, both acid and basic, and a quantitative valuation of its effect will be found in Parts II and III of this chapter.

The same certainty does not pertain to any other effect of this metalloid. Mr. Howe* has ably discussed the whole matter, and I herewith make quotations from The Metallurgy of Steel, and place them in the form of a summary.

(1) The effect of phosphorus on the elastic ratio, as on elongation and contraction, is very capricious.

(2) Phosphoric steels are liable to break under very slight tensile stress if suddenly or vibratorily applied.

(3) Phosphorus diminishes the ductility of steel under a gradually applied load as measured by its elongation, contraction, and elastic ratio when ruptured in an ordinary testing machine, but it diminishes its toughness under shock to a still greater degree, and this it is that unfits phosphoric steels for most purposes.

(4) The effect of phosphorus on static ductility appears to be very capricious, for we find many cases of highly phosphoric steel which show excellent elongation, contraction, and even fair elastic ratio, while side by side with them are others produced under apparently identical conditions but statically brittle.

(5) If any relation between composition and physical properties is established by experience, it is that of phosphorus in making steel brittle under shock; and it appears reasonably certain, though exact data sufficing to demonstrate it are not at hand, that phosphoric steels are liable to be very brittle under shock, even though they may be tolerably ductile statically. The effects of phosphorus on shock-resist-

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* *Loc. cit.*

ing power, though probably more constant than its effects on static ductility, are still decidedly capricious.

The difficulty of detecting a high content of phosphorus, under the ordinary system of physical tests, will be shown by Table 115, which is constructed by comparing the acid open-hearth angles in Table 69, which are of the same ultimate strength and of the same thickness, but which contain different percentages of phosphorus.

Table 115.

Comparative Physical Properties of Low-Phosphorus and High-Phosphorus Steels; Being a Comparison of the Acid Open-Hearth Angles Given in Table 69, which are of the Same Ultimate Strength and of the Same Thickness, but with Different Contents of Phosphorus.

Limits of ultimate strength; lbs per square inch.	No. of group.	Thickness of angle; in inches.	Phosphorus; per cent.	Number of heats.	Average ultimate strength; lbs. per sq. in.	Average elastic limit; lbs. per sq. inch.	Average elastic ratio; per cent.	Average elongation in 8 in.; per cent.	Average reduction of area; per cent.
56000 to 64000	I	$\frac{5}{16}$ to $\frac{3}{8}$	.05 to .07	212	60845	40891	67.21	29.35	57.4
			.07 to .10	50	60064	41143	68.50	28.82	58.4
	II	$\frac{7}{16}$ to $\frac{1}{2}$	.05 to .07	126	60695	39415	64.94	29.23	55.6
			.07 to .10	50	60583	40170	66.30	29.05	56.3
	III	$\frac{9}{16}$ to $\frac{5}{8}$	.05 to .07	81	60558	38645	63.81	28.95	53.8
			.07 to .10	50	61049	39656	64.96	28.98	54.8
	IV	$\frac{11}{16}$ to $\frac{3}{4}$	.05 to .07	121	59906	37478	62.56	29.32	51.3
			.07 to .10	50	59763	38338	64.15	29.60	55.3
64000 to 72000	V	$\frac{5}{16}$ to $\frac{3}{8}$	.05 to .07	40	65656	43713	66.58	27.90	55.0
			.07 to .10	25	66365	44486	67.03	27.19	55.4
	VI	$\frac{7}{16}$ to $\frac{1}{2}$	.05 to .07	29	65631	42191	64.28	27.83	53.7
			.07 to .10	39	65777	42817	65.09	27.49	53.2

Analyzing this record, it will be found that the higher phosphorus gives a higher elastic ratio in all six groups, the difference ranging from 0.45 per cent. to 1.59 per cent., but the elongation and the reduction of area are almost exactly the same in the two kinds of steel. It is the difference between static and shock ductility that makes phosphoric steel so dangerous. In the ordinary testing machine there is no important difference between a pure steel containing less than .04 per cent. of phosphorus, and a common steel with .08 per cent., or a bad steel with .10 per cent.

Not only constructive engineers, but men calling themselves metallurgists, have staked and have lost their reputations in promoting new processes designed to make good finished material out of steel containing high phosphorus. Many a time the metallurgical world has been stirred by some new discovery whereby such metal was induced to show a high ductility in the testing machine, and each time the new process has passed away unwept, unhonored, and unsung as it was rediscovered that static and shock ductility were totally different properties, and that the high phosphorus metal gave lamentable failures as soon as it went beyond the watchful care of its parents and its nurses.

It is true that numerous cases can be cited of rails, plates, etc., containing from .10 to .35 per cent. of phosphorus, which have withstood a long lifetime of wear and adversity; but in the general use of such metal there has been such a large percentage of mysterious breakages that it seems quite well proven that the phosphorus and the mystery are the same.

Much information on the effect of phosphorus may be gathered from a study of high steels. A very severe trial is put upon a cold-chisel or similar tool in the resisting of the continued shock on the sharpened edge, and it is undeniable that each increment of phosphorus has its effect in rendering such a tool brittle. It is true that in this case the steel is quenched and also that it contains a considerable proportion of carbon, but there is no evidence to show that the effect of phosphorus is different when the carbon is high, even though it be true that it is more marked. Neither is there any reason to suppose that the quenching changes its nature, for experiments with high phosphorus steel of low carbon indicate that sudden cooling would rather counteract the influence of phosphorus than enhance it, since it tends to prevent the formation of coarse crystals.

It would seem therefore that the regularly increasing banefulness of phosphorus as the carbon is raised does not portray any change in nature, but that although the effect of the metalloid in lower steels is obscured, its character is the same. No line can be drawn that can be called the limit of safety, since no practical test has ever been devised which completely represents the effect of incessant tremor. For common

structural material the critical content has been placed at .10 per cent. by general consent, but this is altogether too high for railroad bridge work. All that can be said is that safety increases as phosphorus decreases, and the engineer may calculate just how much he is willing to pay for greater protection from accident.

SEC. 149.—*Influence of copper.*—The iron made from the ores of Cornwall, Pa., contains from .75 to 1.00 per cent. of copper, and large quantities of rails have been made from this iron alone, but it has oftener been the custom at eastern steel works to use from 25 to 50 per cent. of this iron in the mixture, the rest being made from foreign ores. Other deposits contain considerable quantities of this element, notably some beds in Virginia, while the ores of Cuba give an iron with about .10 per cent. of copper.

Not only has such metal been put into rails but into all kinds of steel both hard and soft, and large quantities have been worked in puddle furnaces and in foundries, so that the miscellaneous cast-iron, wrought-iron, and steel scrap, throughout the East, is very apt to contain quite an appreciable quantity of copper, and as steelmakers will thus forever have this element to handle, it is of pressing importance that its effect be understood. The necessity for such knowledge is the more marked as it is the custom in certain favored districts to intimate that copper is injurious, although definite proof is always lacking.

Most of the Bessemer steels which are recorded in this book contain from .30 to .50 per cent. of copper, while much of the open-hearth steel is of the same character, and this will be sufficient proof that the best of steel may contain a considerable proportion. If, therefore, it appears from a set of experiments that copper exerts a bad effect, then one of two things follows:

(1) That the experiments have left some factor out of the question.

(2) That the maker of good steel has some trick by which he overcomes the enemy.

It would be a cause for satisfaction if we could boast that the latter supposition were true, but, as a matter of fact, we

have never known that copper injured the cold properties of steel in any way, and it is unnecessary to add that no system has been devised to obviate its influence.

Hard and soft steels of our manufacture have found their way into all channels of trade, and although many failures have come, as they have everywhere, from high carbon, high manganese, or high phosphorus, there have been no cases where it was necessary to invoke the aid of copper. This fact outranks and transcends in value any limited series of tests that might be given. In the same way there is no evidence that copper segregates, experience pointing rather to perfect uniformity. A story has been the rounds of the trade journals of a copper wire which crystallized out in the head of a rail, but, unfortunately, no method is known by which the phenomenon can be duplicated, since such rails might be of great value in electrical work.

Steel may contain up to one per cent. of copper without being seriously affected, but if at the same time the sulphur is high, say .08 to .10 per cent., the cumulative effect is too great for molecular cohesion at high temperatures and it cracks in rolling. This tearing occurs almost entirely in the first passes of the ingot, so that it is of little importance to the engineer who is concerned only with perfect finished material. In the purest of soft steels containing not more than .04 per cent. of either phosphorus or sulphur, the influence of even .10 per cent. of copper may be detected in the less ready welding of seams during the process of rolling, but ordinarily when the sulphur is below .05 per cent. the copper injures the rolling quality very little, even if present in the proportion of .75 per cent. In all cases the cold properties seem to be entirely unaffected.

These conclusions are not founded on any limited series of tests on special alloys; they are the fruit of years of experience in the making of millions of tons of cupriferous steels, and it is quite certain that any baneful influence of this constant companion would have been felt in the many investigations which have been made into the mechanical equation of structural metal.

The quantitative effect of copper upon the tensile strength

of steel was the subject of a paper by Ball and Wingham,* in which they showed that as much as seven per cent. could be alloyed to iron, and that a specimen with four per cent. forged well both hot and cold. It was found also that the alloys were very hard, so that when the content was over seven per cent. the metal could not be cut by a good tool. The experiments showed a considerable increase in tensile strength in the case of higher copper, but no great weight can be given to the determinations, for both the method of making the alloy and the cutting of the test were too crude for conclusive results.

It is not easy to make a comparison between the ductility of high-copper and low-copper steels, for at works using such material it is customary to keep a fairly constant percentage in the mixture rather than to vary between wide limits. A limited number of heats have been grouped together in Table 116, and although the list is not as long as might be desired, it should be considered that the heats were all made within a short period in the same Bessemer, and were all rolled in the same mill.

TABLE 116.

Comparative Physical Properties of Low-Copper and High-Copper Steel Angles.

Made by The Pennsylvania Steel Company, 1893.

Thickness in inches.	Copper; per cent.	Number of heats.	Ultimate strength; pounds per square inch.	Elastic limit; pounds per square inch.	Elongation in 8 inches; per cent.	Reduction of area; per cent.	Elastic ratio; per cent.
5/16	.10	11	61376	44152	27.52	56.30	71.9
	.35	17	60283	43841	27.88	59.01	72.7
3/8	.10	10	58965	42218	28.85	55.50	71.6
	.35	11	59630	43478	29.02	57.86	72.9

It will be noted that no difference is to be found in the ultimate strength between steels with high and low copper, although all the heats were made in the same way as nearly as possible, the workmen not knowing either in the Bessemer department or in the rolling mill what kind of iron was in use.

* *On the Influence of Copper on the Tensile Strength of Steel. Journal I. and S. I.*, Vol. I, 1889, p. 123.

Moreover, the high copper gives a slightly higher elastic ratio, which is a benefit, and also a better elongation and reduction of area. These results can hardly be called conclusive, for the number of heats is too limited, but as the data on high-copper steels are uniform with the much larger number of similar angles given in Table 69, and as the two separate averages for low copper correspond so closely to one another after allowance is made for the two different thicknesses, it seems quite justifiable to conclude that the high copper is not in any way harmful.

Sec. 150.—*Influence of aluminum.*—It is hardly necessary to discuss at length the effect of aluminum upon steel, for although it is often used to quiet the metal, it unites with the oxygen of the bath and passes into the slag. Sometimes a very small percentage remains in steel castings, while it is quite conceivable that other steels may receive a small overdose by mistake, so that Table 117 will be of interest as giving the results of an investigation by Hadfield.*

Table 117.

Physical Properties of Aluminum Steel.

Note.—Size of bars $\frac{11}{16}$ x $\frac{1}{8}$ inch; all samples forged either very well or fairly well except No. 10 which was very shelly. The fractures from Nos. 1 to 7, inclusive, were granular, but Nos. 8, 9, and 10 showed increasing coarse crystallization. All bars bent double cold after annealing except No. 10. Attempts at welding were unsuccessful on samples Nos. 3, 5, and 8.

Group.	Composition; per cent.						Elastic limit; pounds per square inch.	Ultimate strength; pounds per square inch.	Elongation in 2 inches; per cent.	Reduction of area; per cent.	Elastic ratio; per cent.
	C.	Si.	S.	P.	Mn.	Al.					
1	.22	.09	...	...	.07	.15	47040	64960	36.70	62.9	72.4
2	.15	.18	.10	.04	.18	.38	51520	67200	37.85	58.18	76.7
3	.20	.12	...	...	.11	.61	48160	62720	38.40	54.50	76.8
4	.18	.16	.09	.03	.14	.66	45920	64960	33.35	49.86	70.7
5	.17	.10	...	...	.18	.72	49280	62720	40.00	60.74	78.6
6	.26	.15	.08	.04	.11	1.16	51520	73920	32.05	51.46	69.7
7	.21	.18	...	...	.18	1.60	44800	69440	32.70	52.14	64.5
8	.21	.18	.09	.03	.18	2.20	47040	69440	22.75	27.80	67.7
9	.24	.18	...	...	.32	2.24	48160	72800	20.67	24.64	66.1
10	.22	.20	.08	.03	.22	5.60	.....	85120	3.67	3.96	....

After making allowances for the variations in other elements, it will be found that the aluminum has little effect upon the tensile strength, while it does not materially injure the ductility until a content of two per cent. is reached.

* *Aluminum Steel. Journal I. and S. I.*, Vol. II, 1890, p. 161.

These conclusions do not agree with the results which I have found by casting different alloys in the form of six-inch square ingots. The aluminum was added in a solid state and it is quite possible that it was not disseminated uniformly, but the analysis was made on the test bar itself, and the fusible nature of the metal makes it probable that the piece would be reasonably homogeneous. Either two or three ingots were cast from each heat, the first containing either no aluminum or only a trace, while the others were made so as to give fairly rich alloys. The results are given in Table 118.

TABLE 118.

Effect of Aluminum upon the Physical Properties of Steel.

6-inch square ingots, made by The Pennsylvania Steel Company, rolled to 2x3/8 inch.

	Heat number.	Composition; per cent.						Ultimate strength; pounds per square inch.	Elastic limit; pounds per square inch.	Elastic ratio; per cent.	Elongation in 8 inches; per cent.	Reduction of area; per cent.
		C.	P.	Si.	Mn.	S.	Al.					
Soft basic open-hearth steels.	1791	.11	.024	...	.48	.035	.00	48800	33190	68.0	31.25	48.6
		.11	.022	...	.45	.035	.58	56880	41150	72.4	18.25	29.8
	1792	.11	.010	...	.45	.019	.00	46440	31640	68.1	30.00	49.9
		.11	.011	...	.41	.023	.45	53440	36900	69.1	22.50	31.5
	1793	.11	.013	...	.35	...	.00	47160	33490	71.0	31.25	45.8
		.11	...	...	...	...	.50	53900	38530	71.5	27.00	33.7
Soft acid open-hearth steels.	3681	.17	.035	...	.61	.025	.04	58560	39310	67.1	30.00	45.7
		.16	...	...	...	...	.473	63440	42100	66.4	23.00	36.3
		.14	...	...	...	...	.899	64160	39100	60.9	17.50	25.4
	3686	.14	.059	...	.58	.021	.03	65030	43260	66.5	24.00	46.2
		.14	...	...	...	...	.46	67810	47950	70.7	20.00	34.0
		.12	...	...	...	...	1.171	67420	48850	72.5	8.00	15.0
	3688	.12	.034	...	.51	.021	.013	55700	39550	71.0	28.7	51.8
		.12	...	...	...	...	.45	59880	39100	65.3	21.7	40.5
		.13	...	...	...	...	.80	61470	43710	71.1	21.2	34.2
Hard acid open-hearth steels.	3682	.47	.048	.21	.70	.018	.00	107450	65930	61.4	10.0	20.1
		.44	...	...	...	...	.571	110550	72420	65.5	9.2	17.5
		.43	...	...	...	...	1.135	105100	68080	64.8	12.5	21.0
	3683	.54	.044	.31	.75	.020	.00	124040	47830	38.6	10.0	18.0
		.47	...	...	...	...	.37	122080	47680	39.1	...	8.2
		.43	...	...	...	...	.94	128040	47440	37.0	7.5	9.4
	3684	.40	.040	.26	.67	.028	.01	95010	42740	45.0	18.7	41.0
		.36	...	...	...	...	.54	98375	43050	43.8	14.0	24.5
		.38	...	...	...	...	.90	98720	43150	43.7	12.5	20.4
	3685	.40	.046	.30	.68	.031	.00	94700	44610	47.1	16.2	31.3
		.38	...	...	...	...	.52	100055	47240	47.2	13.7	24.1
		.34	...	...	...	...	.73	98480	46910	47.6	12.5	17.5
	3689	.42	.046	.21	.71	.025	.00	90900	53550	58.9	15.5	22.0
		.40	...	...	...	...	.31	94560	59190	62.6	15.0	39.7
		.34	...	...	...	...	.66	96680	59460	61.5	14.7	25.4

The casting and working of such ingots is a regular operation at the works where these experiments were made, and perfect uniformity is always obtained in respect to tensile strength, so that it is probable the variations in bars of the same heat are due to the different contents of aluminum. These changes are as follows:

(1) The addition of one-half of one per cent. of aluminum increases the tensile strength between 3000 and 8000 pounds per square inch, exalts the elastic limit in about the same proportion, and injures very materially the elongation and contraction of area. The effect both upon strength and ductility is more marked in the case of low than in high steels.

(2) The addition of another half of one per cent. does not have much effect upon the ultimate strength or the elastic limit, but it still further decreases the ductility of the metal.

It is stated by Odelstjerna* that the use of aluminum, in the manufacture of steel castings, gives an inferior metal, even though the addition amount to only .002 per cent., and that such steel presents a peculiar fracture, the faces of the crystals being large and well defined. It must be kept in mind, however, that these conclusions apply to one particular kind of practice, and that the use of aluminum, under certain conditions, may produce a most harmful effect, while under other possible conditions the result would be much less marked. Nothing is more difficult than to isolate one factor in a metallurgical equation, and to discover its real value, when it is always associated with complicating and equally powerful agencies.

SEC. 151.—*Influence of arsenic.*—The effect of arsenic upon steel was quite fully investigated several years ago by Harbord and Tucker.† The conclusions given by them may be summarized as follows:

Arsenic, in percentages not exceeding .17, does not appear to affect the bending properties at ordinary temperatures, but above this percentage cold-shortness begins to appear and rapidly increases. In amounts not exceeding .66 per cent., the tensile strength is raised very considerably. It lowers

* *The Manufacture of Open-Hearth Steel in Sweden. Trans. A. I. M. E.,* Vol. XXIV, p. 312.

† *On the Effect of Arsenic on Mild Steel. Journal I. and S. I.,* Vol. I, 1888, p. 183.

the elastic limit, and decreases the elongation and reduction of area in a marked degree. It makes the steel harden much more in quenching, and injures its welding power even when only .093 per cent. is present.

These results have been corroborated by J. E. Stead,* who found that between .10 and .15 per cent. of arsenic in structural steel has no matérial effect upon the mechanical properties; the tenacity is but slightly increased, the elongation and reduction of area apparently unaffected. With .20 per cent. of arsenic, the difference is noticeable, while with larger amounts the effect is decisive. When one per cent. is present, the tenacity is increased, and the elongation and reduction of area both reduced. This increase in strength and diminution in toughness continue as the content of arsenic is raised to 4 per cent., when the elongation and reduction in area become nil.

These experiments are of considerable practical importance, since a great many steels carry an appreciable proportion of arsenic. Some chemists take little cognizance of this fact, and their phosphorus determinations are often too high on account of the presence of arsenic in the phosphorus precipitate. Other analysts take special precautions to avoid this contamination.

Sec. 152.—*Influence of nickel, tungsten, and chromium.*—The first public presentation of the effect of nickel upon steel was a paper by Jas. Riley.† Since that time the properties of nickel steel have become widely known through the experiments by the United States Government on the armor plate manufactured by The Bethlehem Iron Company, and by the Carnegie Steel Company. As it often happens in the case of a new metal, the tendency is to exaggerate its importance. In a paper read before the American Society of Civil Engineers, in June, 1895, I gave the detailed results found by testing nickel steel when rolled into rounds, angles, and plates, and compared them with the records of carbon steel of about the same tensile strength. A condensation of the work will be found in Table 119.

It will be noted that the nickel steel is superior, but in

* *The Effect of Arsenic on Steel. Journal I. and S. I.*, Vol. I, 1895, p. 77.

† *Alloys of Nickel and Steel. Journal I. and S. I.*, Vol. I, 1889, p. 45.

less measure than may be generally supposed. It must be kept in mind, however, that in armor plate, as in many another field, there is sometimes but a very small distance between absolute success and absolute failure, and that it matters little how much margin there is above success, provided there is a margin at all.

Table 119.

The Physical Qualities of Nickel Steel as Compared with Carbon Steel of Similar Tensile Strength.

Note.—All steels were made in an acid open-hearth furnace by The Pennsylvania Steel Company.

Kind of steel.	Composition; per cent. C.	Mn.	P.	S.	Ni.
Nickel	.24	0.78	.032	.027	3.25
Hard forging . .	.30 to .35	.60 to 1.00	.03 to .05	.03 to .05	nil.
Forging	.25 to .30	.60 to .80	.03 to .06	.03 to .07	nil.

Shape of member.	Kind of steel.	Ultimate strength; pounds per square inch.	Elastic limit; pounds per square inch.	Elastic ratio; per cent.	Elongation in 8 inches; per cent.	Elongation in 2 inches; per cent.	Reduction of area; per cent.
Rounds,	Nickel	86015	63575	73.9	20.19	34.00	46.3
	Hard forging .	87663	58055	66.2	16.70	24.44	30.3
	Forging	78066	51793	66.3	23.94	. . .	52.0
Angles,	Nickel	86960	58553	67.3	21.75	39.67	50.5
	Hard forging .	87820	54153	61.7	19.25	34.83	43.3
	Forging	76970	49544	64.4	. . .	. . .	49.6
Universal plates, longitudinal,	Nickel	85773	58410	68.1	21.08	39.25	52.0
	Hard forging .	82773	50163	60.6	20.50	37.67	47.0
	Forging	78996	46654	59.1	26.78	. . .	52.1
Universal plates, transverse,	Nickel	86417	58203	67.4	16.50	28.92	36.1
	Hard forging .	85173	(50000)*	(58.7)*	18.83	23.17	27.4
	Forging	. . . . .	. . . . .	. . . .	. . .	. . .	. . .
Sheared plates, longitudinal,	Nickel	85337	58169	68.2	19.00	35.50	48.3
	Hard forging .	85012	(50000)*	(58.8)*	22.10	39.40	48.4
	Forging	78918	49128	62.3	22.03	. . .	50.8
Sheared plates, transverse,	Nickel	84377	57260	67.9	17.13	32.50	43.4
	Hard forging .	84327	(50000)*	(59.3)*	21.71	37.00	41.3
	Forging	. . . . .	. . .	. . . . .	. . .	. . .	. . .

There are other elements used to make special alloys with iron, some of these metals being of considerable importance. Tungsten and chromium are both employed to give tool steels extreme hardness, their peculiar characteristic being that no

* Approximate; could not determine accurately.

quenching or tempering is required. These alloys, however, do not come under the head of structural material, and will therefore not be considered here.

SEC. 153.—*Influence of oxide of iron.*—The last step in the making of a heat of steel is the addition of the recarburizer to wash the oxygen from the bath, but this action is not perfect, and the exact relation is not generally understood. The amount of oxygen taken from the metal will evidently be measured by the amount of manganese and other metalloids that are burned during the reaction, and this amount was shown in Section 77 to be a function of the quantity which is added.. In other words, if there is a reduction in the percentage of manganese which is added to an open-hearth bath at the time of tapping, there will be a reduction in the amount of manganese which will be oxidized, and this proves conclusively that the reaction is not perfect, and that an increasing amount of oxygen must remain in the metal as the content of manganese decreases; but a reasonable proportion of this oxygen can hardly exert any marked deleterious influence, else the fact would long ago have been known in some more definite form than the suppositions and theories which are occasionally founded on exceptional phenomena.

Assuming as certain that high oxygen will more likely be found in steels both low in manganese and in oxidizable metalloids, it may reasonably be expected that any bad effect it may exert will be seen in the softest products of the basic open-hearth and in the purest of acid steel. On the contrary, it is well known that the reverse is true, and that the ductility increases as the condition of pure iron is approached.

Some people imagine that it is not well to take all the impurities out of iron, their thesis having been forcibly, though somewhat inelegantly, expressed in the saying that a shirt can be ruined by too much scrubbing. Unfortunately, the simile is entire worthless, for the purification of steel is not a process of washing, although often so called. Dephosphorization does not consist in mechanically removing certain foreign ingredients, but in placing the metal in contact with a slag of such a character that the metalloids find in it a more congenial home, and although it is true that over-

oxidation assists the purification, it is not at all a necessary adjunct, since the transfer of allegiance may be effected by a slag moderately rich in lime, combined with the normal oxidizing influences.

In a discussion of a paper by Webster, which will be referred to at length in Part II of this chapter, H. D. Hibbard* deduced the fact that oxide of iron reduces the tensile strength of very soft metal by several thousand pounds. I cannot endorse this conclusion, but offer Table 120 as evidence to the contrary.

TABLE 120.

Individual Records of Heats Composing Group 63 in Table 121.

Heat number.	Carbon by combustion; per cent.	Carbon by color; per cent.	Phosphorus; per cent.	Manganese; per cent.	Sulphur; per cent.	Copper; per cent.	Elastic limit; pounds per square inch.	Ultimate strength; pounds per square inch.	Elastic ratio; per cent.
4669	. . .	.04	.007	.02	.024	.10	28420	45620	62.3
4809	. . .	.04	.007	.05	.019	.05	30640	46310	66.2
4930	. . .	.04	.007	.04	.021	.06	24370	46000	53.0
4932	. . .	.04	.011	.04	.029	.04	25810	46480	55.5
4971	. . .	.03	.010	.05	.032	.14	26780	47140	56.8
4972	. . .	.04	.010	.04	.021	.10	27920	47000	59.4
Average,	.025	.04	.009	.04	.024	.08	27323	46425	58.9

These heats were made in a basic open-hearth furnace, and their regularity both in chemical and physical character shows that we are dealing with a normal and definite metal and not with an accidental product. They were purposely made with the lowest possible content of manganese, and it seems positively certain that the steel must be saturated with oxygen.

These six heats constitute Group 63 in Table 121, and by the most casual inspection, as well as by a glance at Curve *AA* in Figure XIX, it will be plain that these steels are much stronger than would be expected as compared with those containing more carbon. It may be that the first increments of carbon have less strengthening effect than further additions, or it may be that the first increments of manganese have a marked weakening effect, but it is more probable that the oxide of iron increases the ultimate strength.

* *Trans. A. I. M. E.*, Vol. XXI, p. 999.

PART II.

EFFECT OF CERTAIN ELEMENTS AS DETERMINED BY SPECIAL MATHEMATICAL INVESTIGATIONS.

INTRODUCTORY NOTE.—The sections immediately after No. 154, from 155 to 159, inclusive, may be omitted by the general reader. They discuss an investigation upon a series of steels by the method of least squares, and it was originally intended that they should close the chapter, but while the proofsheets of the book were coming from the press, the calculations were completed on an entirely new series. This new work sheds much light on some points that were obscure, and gives authority for more positive statements.

This increased knowledge does not arise from any superiority of the second investigation, but simply from the fact that the basis of work was doubled, and the validity of the results correspondingly enhanced. It has been deemed proper, therefore, to omit many deductions that had been drawn from the first series, but the most important of these conclusions are given in Section 159 in precisely the form in which they were worded before the new series was contemplated.

The careful student will find it necessary to read the following sections to understand the steps involved, and to know why certain elements have been omitted from the formulæ, but those less curious may pass to Part III, which embraces the latest investigations on both the old and the new series, while in Section 165 will be found a synopsis of the whole argument and the conclusions drawn therefrom.

SEC. 154.—*Investigations by Webster on the influence of the metalloids.*—The most comprehensive and systematic study of the physical formula of steel has been carried out by W. R. Webster.* He has used the long and laborious method of successive approximations, and by "cutting and trying" has found the effect of each element upon the ultimate strength, as well as the effect of the thickness and finishing temperature. The results are given by him as follows:

.01 per cent. of sulphur increases the tensile strength 500 pounds per square inch.

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* *Observations on the Relations between the Chemical Constitution and Physical Character of Steel. Trans. A. I. M. E.*, Vol. XXI, p. 766, and Vol. XXIII, p. 113; also *Journal I. and S. I.*, Vol. I, 1894, p. 328.

.01 per cent. of manganese has an effect which varies with each increment as follows, the values being expressed in pounds per square inch:

An increase in percentage	gives an increment of	making a total increase in strength over metal with no manganese of
from .00 to .15	3600	3600
" .15 to .20	1200	4800
" .20 to .25	1100	5900
" .25 to .30	1000	6900
" .30 to .35	900	7800
" .35 to .40	800	8600
" .40 to .45	700	9300
" .45 to .50	600	9900
" .50 to .55	500	10400
" .55 to .60	500	10900
" .60 to .65	500	11400

.01 per cent. of phosphorus has an effect which varies according to the amount of carbon present:

With .08 per cent. of carbon it is 800 pounds per square inch.
" .09 " " " " " " 900 " " " "
" .10 " " " " " " 1000 " " " "
" .11 " " " " " " 1100 " " " "
" .12 " " " " " " 1200 " " " "
" .13 " " " " " " 1300 " " " "
" .14 " " " " " " 1400 " " " "
" .15 " " " " " " 1500 " " " "
" .16 " " " " " " 1500 " " " "
" .17 " " " " " " 1500 " " " "

Carbon is credited with a constant effect of 800 pounds for each .01 per cent.

Mr. Webster has constructed, from these values, a table showing the strength of metal containing different proportions of carbon and phosphorus, from which, as a basis, the strength of a given steel may be found by allowing for the content of manganese and sulphur. This table presents a curious anomaly, as will be shown by the following excerpt:*

Estimated Ultimate Strengths; Pounds per Square Inch; per Webster.

Carbon; per cent.	.07	.08	.09	.10	.11	.12	.13	.14	.15	.16	.17	.18
P = .00 per ct.	40350	41150	41950	42750	43550	44350	45150	45950	46750	47550	48350	49150
P = .03 per ct.	42750	43550	44650	45750	46850	47950	49050	50150	51250	52050	52850	53650
P = .06 per ct.	45150	45950	47350	48750	50150	51550	52950	54350	55750	56550	57350	58150
P = .10 per ct.	48350	49150	50950	52750	54550	56350	58150	59950	61750	62550	63350	64150

An examination of these figures reveals two absolutely irreconcilable conditions, for Mr. Webster takes as his starting point the dictum that carbon is a constant, and proceeds to construct a table in which it is not a constant at all, and

* *Journal I. and S. I.* Vol. I, 1894, p. 338.

in which it is not even constantly irregular. By his own calculation a steel of .06 per cent. phosphorus and .10 per cent. carbon is strengthened 1400 pounds by the addition of .01 per cent. of carbon, while with .10 per cent. phosphorus it is strengthened 1800 pounds by the same addition. Assuredly, this is not a constant effect. Moreover, carbon does not even have a constant effect with the same content of other metalloids, for, with .10 per cent. of phosphorus, an increase in carbon from .07 to .08 per cent. raises the strength 800 pounds, while an increase from .08 to .09 per cent. strengthens it 1800 pounds.

It would be just as correct to conclude from these results that phosphorus is a constant and carbon a variable, as to say that carbon is a constant and phosphorus a variable. The changing values which it would be necessary to assign to carbon to fulfill the first assumption would be no more arbitrary and hypothetical than the changing values assigned to phosphorus by Mr. Webster, or the changing values which he has assigned to manganese. Thus the table which has been given is entirely indecisive, since it can be translated into two diametrically opposite readings, and it must be acknowledged that one empirical formula is as good as another, provided the same answers are obtained from both.

This curious contradiction of the premises by the conclusion can only arise from some erroneous hypothesis in the values assigned to the different elements, for in the construction of such equations it is plain that an error in one factor must be atoned for by an opposite and equal error in another factor. If this reasoning be true, then very little faith can be attached to the formula as an expression of fundamental laws, however accurately the mathematical results may coincide with observations.

It is to be regretted that the earnest endeavor of Mr. Webster to write the physical formula should have been hampered by the necessity of working on sheared plates, which are finished under greater variations of temperature than angles or bars, and furthermore that these plates were of basic Bessemer steel, a material which would not be chosen for its regularity. By correcting for thickness and finishing

temperature, Mr. Webster has shown that about 90 per cent. of the heats investigated came within 5000 pounds per square inch of what his equation calls for.

This is a very satisfactory result, and it is not in a spirit of hypercriticism (for my own results, to be given later, display examples of the same character), but from a strictly scientific point of view, that attention is called to the very unpleasant corollary that one charge out of every ten does not give results within 5000 pounds. Some of these undoubtedly are vitiated by wrong chemical determinations, for the carbon was determined by color, and this gives only approximate results; on others there might well be an error in estimating the finishing temperature; on others there would be mistakes in measuring and testing; while some pieces, perhaps, did actually show those peculiarities which we call abnormal, which are ascribed sometimes to oxide of iron, sometimes to nitrogen, and not infrequently to the devil, but which grow less numerous as we learn more of our art.

I can not believe that the complicated formula of Mr. Webster represents actual conditions, and the remainder of this chapter will attempt to show that a reasonably accurate empirical equation of steel may be written without the introduction of such manifold variations, and by the use of constant values for each element within the limits usually obtaining in structural metal. It will also be shown that the first increments of manganese do not add greatly to the strength of steel, since low-manganese metal is stronger than would be indicated by a formula that applies to steels containing higher percentages of this element.

SEC. 155.—*Investigations on Pennsylvania Steel Company steels by the method of averaging groups of preliminary tests.*—I believe that the true way to investigate the influence of the metalloids upon the physical qualities of steel is to make groups of heats so as to avoid the determinative errors in any one charge. The method of forming these groups in the following investigation is of such importance that it is necessary to give a full description. It is the custom at The Pennsylvania Steel Works to make a preliminary test of every open-hearth heat, and it is found that this test is almost invariably a reliable exponent of the charge from which it comes. In

the rolling of plates, angles, and miscellaneous shapes, the thickness of the piece and the finishing temperature have a great effect upon the result, but in this test-piece the conditions of heating and working are so constant that the results as shown by the testing machine reflect only the influence of variations in the chemical equation.

Having preserved the broken bars for a considerable time, there were at hand 575 pieces of acid steel below 80,000 pounds ultimate strength, 1160 pieces of basic steel below 70,000 pounds, and 145 pieces of acid steel above 80,000 pounds. In addition to the ultimate strength, the content of manganese, sulphur, and phosphorus was on record for each piece.

Taking the low-acid steels as one basis of work, a further separation was made according to the tensile strength; for example, in the case of the low-acid steels there were 148 heats between 58,000 and 60,000 pounds, and these were considered a subdivision. This was again divided, the heats being arranged according to their chemical composition. Thus there were 18 heats which showed lower manganese than the rest, and these were averaged to give Group 8 in Table 121. There were 13 heats showing high manganese, and these gave Group 16. The low-sulphur heats gave Group 24, the high sulphur Group 17. The low phosphorus gave Group 25, the high phosphorus Group 19, while there were 72 heats which did not show a high content of any element, and these form Group 15.

Oftentimes it would happen that a charge which contained high manganese would show either a low or a high percentage of some other element, and hence would appear in two or more groups, so that the total number of heats in the table is larger than the number of test-pieces.

After forming these groups, the average manganese, sulphur, phosphorus, and ultimate strength of each were calculated from the records, while the average carbon, silicon, and copper were determined by weighing an equal quantity of drillings from each bar and making a chemical analysis, the carbon being determined by combustion. Since each member of a group contained nearly the same percentage of carbon, it is evident that very little error is introduced by this system of average, while it assuredly tends to hide the idiosyncrasies of any one heat.

Table 121.

List of Groups Used in Determining the Effect of Certain Elements upon the Tensile Strength of Steel, together with the Formulæ Obtained therefrom by the Method of Least Squares.

NOTE.—All figures relating to ultimate strength are expressed in pounds per square inch.

Number of formula.	Kind of steel.	Effect of .001 per cent. upon the ultimate strength.			
		Carbon.	Manganese.	Phosphorus.	Iron.
1	Acid,	+152.9212	—3.902156	+131.6955	+0.3432669
2	Basic,	+103.4560	+5.298315	+ 94.08509	+0.3899613

	Number of group.	Number of heats in group.	Composition; per cent.							Average ultimate strength of group.	Formula No. 1.		
			Carbon, by combustion.	Silicon.	Manganese.	Sulphur.	Phosphorus.	Copper.	Iron, by difference.		Ult. strength as calculated from formula.	Diff. bet. actual and calculated ultimate strength.	Calculated str. from iron and carbon only.
Division I. Low acid open-hearth steel.	1	6	.082	.006	.290	.034	.034	.120	99.434	52090	50018	—2072	46672
	2	12	.105	.009	.380	.059	.074	.180	99.193	57375	58369	+ 994	50106
	3	11	.109	.008	.310	.036	.066	.140	99.331	57310	58248	+ 938	50765
	4	12	.109	.007	.380	.048	.082	.150	99.224	57430	60045	+2615	50729
	5	38	.113	.009	.430	.038	.061	.130	99.219	57140	57694	+ 554	51339
	6	11	.113	.007	.480	.046	.096	.180	99.078	62870	62060	— 810	51290
	7	5	.115	.007	.490	.029	.037	.090	99.232	55450	54610	— 840	51649
	8	18	.115	.013	.300	.043	.069	.170	99.290	58780	59585	+ 805	51669
	9	12	.116	.005	.590	.025	.034	.100	99.130	56830	53942	—2888	51767
	10	19	.116	.015	.500	.069	.082	.190	99.028	60870	60580	— 290	51732
	11	9	.116	.013	.470	.057	.089	.170	99.085	62610	61638	— 972	51752
	12	18	.117	.018	.330	.039	.073	.200	99.223	61190	60278	— 912	51952
	13	17	.117	.005	.450	.049	.099	.160	99.120	61430	63198	+1768	51916
	14	19	.118	.005	.590	.030	.035	.100	99.122	56990	54377	—2613	52070
	15	72	.118	.007	.420	.045	.075	.140	99.195	59110	60333	+1223	52095
	16	13	.118	.008	.560	.044	.063	.140	99.067	59350	58163	—1187	52051
	17	15	.118	.007	.450	.064	.081	.170	99.110	59260	60977	+1717	52066
	18	15	.118	.014	.570	.056	.076	.180	98.986	60900	59808	—1092	52023
	19	21	.119	.009	.420	.051	.090	.140	99.171	59310	62453	+3143	52240
	20	15	.119	.017	.430	.028	.065	.160	99.181	61020	59125	—1895	52243
	21	96	.119	.009	.440	.043	.077	.160	99.152	61130	60657	— 473	52233
	22	19	.123	.014	.440	.030	.063	.160	99.170	59110	59431	+ 321	52851
	23	6	.129	.008	.490	.050	.118	.160	99.045	65020	67354	+2334	53726
	24	11	.131	.012	.470	.033	.051	.130	99.173	60690	58958	—1732	54075
	25	13	.134	.015	.480	.035	.045	.150	99.141	58820	58577	— 243	54523
	26	12	.138	.021	.360	.041	.077	.140	99.223	62940	63899	+ 959	55163
	27	38	.140	.016	.480	.042	.077	.180	99.065	62890	63682	+ 792	55415
	28	10	.143	.006	.390	.045	.086	.200	99.130	64880	65700	+ 820	55891
	29	10	.147	.012	.540	.024	.056	.160	99.061	63210	61752	—1458	56484
	30	12	.151	.012	.640	.033	.051	.130	98.983	62650	61288	—1362	57069
	31	7	.151	.005	.490	.055	.088	.160	99.051	64950	66769	+1819	57092
	32	12	.156	.008	.570	.035	.070	.170	98.991	65180	64830	— 350	57836
	33	8	.171	.011	.630	.026	.036	.100	99.026	62850	62425	— 425	60142
	34	4	.178	.008	1.000	.043	.076	.140	98.555	71930	67157	—4773	61051
	35	8	.183	.014	.680	.030	.027	.100	98.966	65100	62859	—2241	61956
	36	9	.185	.008	.760	.028	.038	.130	98.851	65590	64261	—1329	62223
	37	6	.193	.009	.670	.020	.036	.100	98.972	65280	65614	+ 334	63488
	38	5	.198	.013	.610	.032	.060	.140	98.947	69970	69765	— 205	64244
	39	8	.207	.012	.790	.045	.067	.150	98.729	71210	71286	+ 76	65545
	40	8	.212	.010	.820	.039	.073	.140	98.706	71870	72716	+ 846	66302
	41	4	.213	.012	.700	.019	.046	.140	98.870	69750	69837	+ 87	66511
	42	5	.225	.015	.990	.048	.077	.220	98.425	78700	74471	—4229	68193
	43	5	.235	.016	.750	.027	.037	.140	98.795	71170	71796	+ 626	69850
	44	12	.240	.009	.760	.030	.054	.140	98.767	72320	74754	+2434	70605
	45	7	.242	.010	.860	.049	.076	.190	98.573	78020	77497	— 523	70844
	46	6	.282	.009	.660	.033	.053	.160	98.803	76830	81444	+4614	77040
	47	6	.282	.010	.770	.023	.043	.140	98.732	76940	79673	+2733	77015

Table 121.—Continued.

Division	Number of group.	Number of heats in group.	Composition; per cent. Carbon, by combustion.	Silicon.	Manganese.	Sulphur.	Phosphorus.	Copper.	Iron, by difference.	Average ultimate strength of group.	Formula No. 1. Ult. strength as calculated from formula.	Diff. bet. actual and calculated ultimate strength.	Calculated str. from iron and carbon only.
Division II. High acid open-hearth steel.	48	7	.306	.010	.790	.034	.050	.090	98.720	82680	84183	+1503	80681
	49	7	.333	.220	.650	.026	.041	.080	98.650	87410	87649	+ 239	84786
	50	11	.341	.020	.850	.034	.045	.110	98.600	86980	88602	+1622	85992
	51	8	.374	.030	.830	.035	.057	.120	98.554	90750	95291	+4541	91023
	52	14	.390	.220	.680	.023	.034	.080	98.573	92630	95300	+2670	93476
	53	6	.427	.028	.860	.026	.027	.100	98.532	99300	99320	+ 20	99120
	54	17	.428	.220	.650	.023	.036	.080	98.563	97270	101488	+4218	99284
	55	16	.438	.220	.690	.026	.033	.130	98.463	102900	102432	— 468	100779
	56	14	.477	.240	.690	.025	.030	.080	98.458	107300	107999	+ 699	106741
	57	20	.480	.230	.690	.022	.032	.060	98.486	111740	108731	—3009	107209
	58	13	.480	.090	1.120	.044	.106	.190	97.970	121210	116621	—4589	107032
	59	18	.507	.061	1.185	.047	.110	.180	97.910	126800	121003	—5797	111140
	60	10	.527	.250	.720	.027	.032	.070	98.374	116980	115763	—1217	114358
	61	10	.554	.230	.680	.022	.032	.090	98.392	122950	120054	—2896	118493
	62	9	.555	.090	1.130	.042	.109	.190	97.884	123620	128417	+4797	118472
											Formula No. 2.		
Division III. Basic open-hearth steel.	63	6	.025	.005	.040	.024	.009	.080	99.817	46420	42570	—3850	41511
	64	4	.045	.006	.270	.045	.010	.110	99.514	47550	45834	—1716	43462
	65	4	.050	.009	.330	.026	.007	.190	99.388	47060	46337	— 723	43939
	66	4	.050	.005	.360	.031	.022	.150	99.382	47610	47905	+ 295	43928
	67	16	.052	.012	.350	.054	.019	.140	99.373	49010	47773	—1237	44131
	68	6	.055	.015	.340	.019	.008	.100	99.463	47130	47031	— 99	44477
	69	7	.055	.005	.220	.030	.012	.140	99.538	47570	46801	— 769	44506
	70	12	.058	.005	.340	.029	.011	.140	99.417	47010	47606	+ 596	44769
	71	8	.061	.006	.460	.025	.016	.140	99.292	47300	48973	+1673	45031
	72	18	.062	.008	.210	.036	.015	.120	99.549	48980	47758	—1222	45235
	73	6	.065	.008	.360	.080	.014	.180	99.293	49770	48670	—1100	45445
	74	17	.070	.013	.350	.034	.031	.140	99.362	49250	50760	+1510	45989
	75	22	.074	.005	.360	.023	.007	.130	99.401	48830	48984	+ 154	46418
	76	19	.074	.009	.390	.018	.013	.100	99.396	49150	49706	+ 556	46416
	77	13	.076	.011	.410	.062	.018	.180	99.243	50880	50429	— 451	46564
	78	94	.078	.003	.380	.031	.016	.110	99.382	49090	50343	+1253	46825
	79	15	.081	.005	.540	.031	.016	.130	99.197	49220	51429	+2209	47063
	80	17	.083	.005	.420	.029	.008	.130	99.325	50910	50298	— 612	47320
	81	16	.083	.006	.570	.035	.017	.110	99.179	51060	51882	+ 822	47263
	82	26	.084	.009	.250	.033	.021	.140	99.463	50900	50777	— 123	47477
	83	23	.085	.014	.380	.032	.036	.140	99.313	51140	52922	+1782	47522
	84	21	.090	.006	.400	.018	.015	.100	99.371	51200	51592	+ 392	48062
	85	121	.093	.006	.400	.032	.019	.130	99.320	51030	52259	+1229	48352
	86	17	.093	.006	.400	.038	.040	.160	99.263	53020	54213	+1193	48330
	87	21	.094	.011	.430	.036	.046	.180	99.203	54800	55016	+ 216	48410
	88	14	.096	.007	.440	.065	.023	.160	99.209	53000	53115	+ 115	48619
	89	19	.099	.012	.280	.035	.029	.160	99.385	52950	53210	+ 260	48998
	90	14	.100	.009	.660	.029	.019	.150	99.033	53380	54249	+ 869	48965
	91	5	.102	.010	.470	.087	.027	.150	99.154	53600	54249	+ 649	49219
	92	15	.103	.013	.440	.064	.027	.130	99.223	54950	54221	— 729	49349
	93	15	.108	.008	.420	.019	.018	.110	99.317	52910	53822	+ 912	49903
	94	125	.109	.010	.430	.031	.021	.120	99.279	52980	54246	+1266	49992
	95	103	.112	.005	.420	.034	.025	.160	99.244	54880	54866	— 14	50288
	96	23	.115	.009	.430	.031	.009	.130	99.276	52750	53736	+ 986	50611
	97	13	.117	.007	.460	.035	.053	.130	99.198	57210	58211	+1001	50788
	98	15	.118	.014	.490	.057	.033	.140	99.148	56980	56573	— 407	50872
	99	18	.120	.004	.430	.018	.020	.120	99.288	54860	55293	+ 433	51133
	100	7	.121	.008	.540	.032	.056	.140	99.103	60580	59294	—1286	51165
	101	11	.125	.012	.670	.038	.025	.130	99.000	56680	57440	+ 760	51538
	102	10	.125	.019	.540	.060	.036	.110	99.110	58790	57829	— 961	51581
	103	16	.126	.008	.620	.028	.024	.140	99.054	55090	57206	+2116	51663
	104	19	.131	.008	.300	.029	.022	.130	99.380	54690	55966	+1276	52307
	105	20	.132	.006	.390	.027	.009	.130	99.306	54890	55295	+ 405	52382
	106	63	.132	.010	.470	.033	.028	.190	99.137	56870	57440	+ 570	52316
	107	9	.134	.016	.510	.036	.055	.110	99.139	59110	60400	+1290	52523
	108	15	.136	.009	.310	.029	.024	.130	99.362	57010	56718	— 292	52817

TABLE 121.—Continued.

	Number of group.	Number of heats in group.	Composition; per cent.							Average ultimate strength of group.	Formula No. 2.		
			Carbon, by combustion.	Silicon.	Manganese.	Sulphur.	Phosphorus.	Copper.	Iron, by difference.		Ult. strength as calculated from formula.	Diff. bet. actual and calculated ultimate strength.	Calculated str. from iron and carbon only.
Division III. Basic open-hearth steel.	109	11	.137	.020	.720	.037	.033	.180	98.873	59110	59650	+ 540	52730
	110	6	.142	.017	.530	.058	.029	.120	99.104	60570	58874	—1696	53337
	111	10	.144	.008	.500	.020	.026	.120	99.182	58860	58670	— 190	53575
	112	37	.144	.015	.520	.034	.028	.130	99.129	58970	58944	— 26	53554
	113	14	.146	.015	.440	.019	.023	.110	99.247	57030	58302	+1272	53807
	114	21	.147	.005	.430	.027	.011	.100	99.280	57060	57237	+ 177	53923
	115	7	.151	.016	.680	.029	.024	.180	98.920	60870	60058	— 812	54197
	116	9	.152	.008	.640	.034	.045	.170	98.951	63480	61937	—1543	54312
	117	10	.153	.011	.460	.027	.012	.100	99.237	58970	58094	— 876	54527
	118	13	.153	.008	.530	.034	.030	.160	99.085	60770	60099	— 671	54468
	119	12	.155	.012	.390	.029	.020	.120	99.274	59110	58697	— 413	54749
	120	6	.158	.012	.820	.032	.027	.170	98.781	63400	61752	—1648	54867
	121	8	.164	.018	.570	.046	.031	.160	99.011	63740	61514	—2226	55577
	122	7	.173	.009	.530	.021	.021	.110	99.136	60810	61341	+ 531	56557
	123	11	.180	.012	.560	.029	.026	.150	99.043	63110	62658	— 452	57245
	124	10	.181	.006	.480	.031	.011	.100	99.191	60740	60984	+ 244	57406
	125	8	.181	.011	.370	.028	.019	.070	99.321	60870	61205	+ 335	57457
	126	5	.185	.039	.720	.049	.043	.110	98.854	67570	65549	—2021	57689
	127	5	.190	.008	.720	.037	.047	.170	98.828	66480	66433	— 47	58196
	128	5	.196	.025	.860	.032	.029	.170	98.688	67480	66047	—1433	58762
	129	10	.199	.012	.620	.030	.025	.120	98.994	66820	64829	—1991	59192
	130	7	.204	.007	.450	.028	.010	.120	99.181	63600	63107	— 493	59782
	131	8	.210	.010	.530	.020	.018	.130	99.082	63740	64866	+1126	60364
	132	6	.215	.005	.420	.024	.011	.160	99.165	63470	64174	+ 704	60914
	133	6	.231	.029	.360	.025	.012	.120	99.223	67530	65628	—1902	62591
	134	5	.233	.008	.490	.020	.021	.130	99.098	67560	67322	— 238	62750
	135	5	.260	.060	.310	.025	.014	.100	99.231	68470	68554	+ 84	65595
	136	5	.311	.080	.440	.029	.020	.070	99.050	73010	75013	+2003	70800
	137	5	.338	.025	.620	.026	.017	.100	98.874	77950	78410	+ 460	73525

By this system of combination the low-acid steels gave 47 groups, which are given in Division I, Table 121, and are plotted in Curve *AA*, Figure XVIII. The high-acid steels gave 15 groups, which are given in Division II, Table 121, and are plotted in Curve *BB*, Figure XVIII. The basic steels gave 75 groups, which are given in Division III, Table 121, and are plotted in Curve *AA*, Figure XIX. In these graphic representations the ordinates are the ultimate strength per square inch, and the abscissas the percentage of carbon, the latter element being selected because it is universally recognized as the controlling component.

SEC. 156.—*Quantitative valuation of the elements by the method of least squares.*—It is certain that carbon increases the strength of steel when present in small proportions, but that after a certain content is reached (say about 1.00 per cent.) there is no increase in cohesive power from a further addition. It will also be granted that this point is not a

sudden break in the line, but that the effect of each unit of carbon decreases as it is approached. If this relation holds good throughout the whole series of alloys, then each successive increment of carbon will have a less effect from the starting point of pure iron.

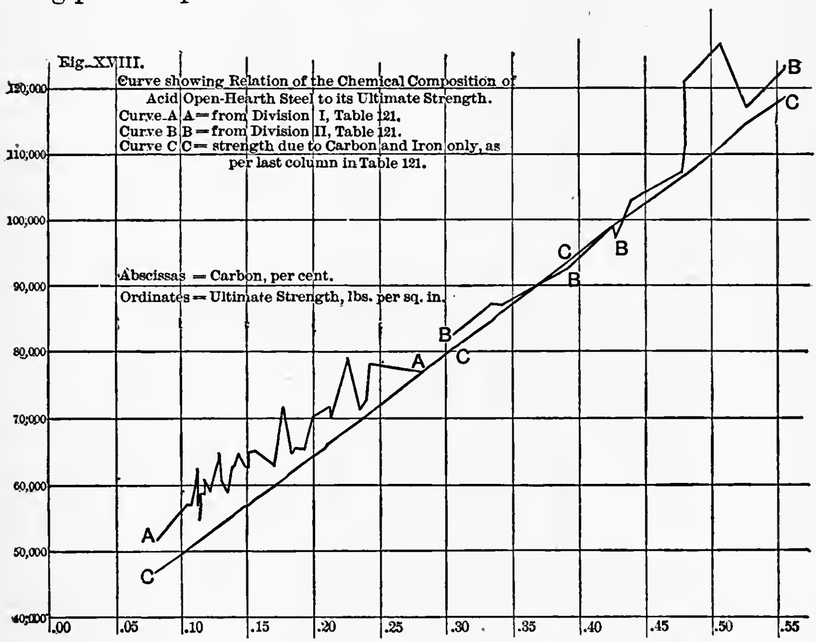

FIG. XVIII.—CURVES SHOWING RELATION OF THE CHEMICAL COMPOSITION OF ACID OPEN-HEARTH STEEL TO THE ULTIMATE STRENGTH.

It is also possible for the same reasons that every other metalloid will follow the same rule, so that the influence of each separate alloyed element will be represented by a curve. This may be an arc of a circle, or a parabola, or a cycloid, or a broken line; it may be different in degree or different in nature in the case of each element; and it may vary in degree or even in nature with changes in the proportions of the associated elements. But it will be assumed in this investigation that within the narrow limits of the divisions of the table, the effect of a regular increase in the percentage of each metalloid would be represented by a straight line.

In other words, that an increase of carbon from .20 to .21 per cent. gives the same increment in strength as an increase from .10 to .11 per cent.

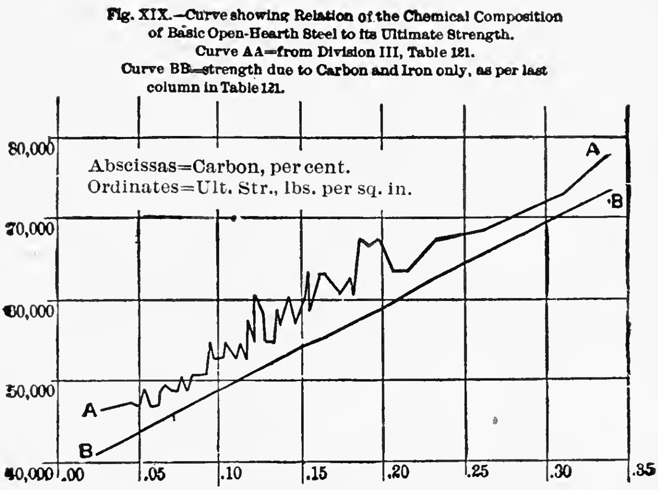

FIG. XIX.—CURVES SHOWING RELATION OF THE CHEMICAL COMPOSITION OF BASIC OPEN-HEARTH STEEL TO THE ULTIMATE STRENGTH.

If this last assumption be true, then the seemingly erratic deviations of the curves in Figure XVIII and Figure XIX from a straight line are due to variations in the associated percentages of silicon, manganese, sulphur, phosphorus, and copper. It seems possible to find the effect of these elements by the method of least squares. Each group may be regarded as an equation containing seven unknown quantities, the combined effect of which produces a certain ultimate strength. If A is written for the effect of .001 per cent. of carbon upon the ultimate strength, B for silicon, C for manganese, D for sulphur, E for phosphorus, F for copper, and G for iron, then Group I will take the following form:

$$82\ A + 6\ B + 290\ C + 34\ D + 34\ E + 120\ F + 99434\ G = 52000.$$

Similarly the 47 groups of low-acid steels furnish 47 equations of condition, as they are called, and from these may be deduced seven normal equations containing seven unknown quantities.

These normal equations being solved by ordinary algebraic methods give the values of A, B, C, D, E, F, and G, which will most nearly fit the original equations of condition. The method by which the normal equations are deduced is explained in the following formula:

Multiply each equation by the coefficient of A *in that equation, then add together the resulting equations for a new equation; then multiply each equation by the coefficient of* B *in that equation, and, as before, form the sum of the resulting equations. Continue the process with the coefficients of each of the unknown quantities. The number of resulting normal equations will be equal to that of the unknown quantities, and the values of the unknown quantities deduced therefrom will, as above stated, be the most probable values.*

NORMAL EQUATIONS FROM LOW ACID OPEN-HEARTH HEATS.

Equation from A; 1,210,191 A + 76,504 B + 4,298,830 C + 272,436 D + 450,670 E + 1,074,560 F + 710,516,809 G = 471,142,635.

Equation from B; 76,504 A + 5,845 B + 274,330 C + 19,254 D + 31,696 E + 75,260 F + 48,817,111 G = 31,631,465.

Equation from C; 4,298,830 A + 274,330 B + 15,861,200 C + 1,002,980 D + 1,644,430 E + 3,887,300 F + 2,581,030,930 G = 1,697,750,700.

Equation from D; 272,436 A + 19,254 B + 1,002,980 C + 78,962 D + 128,102 E + 286,420 F + 183,011,846 G = 117,362,985.

Equation from E; 450,670 A + 31,696 B + 1,644,430 C + 128,102 D + 215,997 E + 474,310 F + 300,954,795 G = 194,090,210.

Equation from F; 1,074,560 A + 75,260 B + 3,887,300 C + 286,420 D + 474,310 E + 1,093,400 F + 697,108,750 G = 450,996,700.

Equation from G; 710,516,809 A + 48,817,111 B + 2,581,030,930 C + 183,011,846 D + 300,954,795 E + 697,108,750 F + 460,910,659,759 G = 296,665,604,300.

These equations have been worked out without the use of logarithms and are absolutely accurate, since the conditions of the problem render possible a perfect proof. The iron being determined by difference, it follows that the sum of the coefficients in each equation of condition is 100,000, and since each coefficient in each equation is successively multiplied by every other one in the same equation to form new coefficients, it follows that the sum of the resultant coefficients for each equation of condition must be the square of 100,000, while the sum of all the equations derived from the 47 equations of condition will be 47 times this number, or 470,000,000,000, and this is exactly the sum of all the coefficients in the above seven normal equations.

In the subsequent work of finding the values of the unknown quantities it is out of the question to sustain this strict accuracy, as by the continual combination of terms the final step would involve the multiplication of two numbers, each of which would contain nearly 150 integers. Seven-place logarithm tables have therefore been used, and seven integers have been kept in all corresponding numbers. This care is necessary in determining seven unknown quantities, since the number of operations is so great that the accumulated logarithmic error is of considerable importance.

It is necessary also to keep in mind that the iron is determined by difference, so that it must bear all the inaccuracies that occur in the determination of the other elements. Moreover, it is a false assumption that this "difference" is entirely made up of pure iron, for there are certain appreciable portions of oxygen and arsenic, with traces of other elements like nickel, cobalt, nitrogen, etc. It is difficult to say how much this fact impairs the value of the results.

Following is the result of the solution for the low acid open-hearth heats, the number in each case expressing the effect of .001 per cent. of the element upon the tensile strength, in pounds per square inch.

Carbon = + 135.6419; Silicon = + 71.75700.
Manganese = — 2.066168; Sulphur = — 37.77523.
Phosphorus = + 117.6217; Copper = + 7.389871.
Iron = + 0.3655429.

The values are given in each case to seven figures, although at first sight this may seem an absurd refinement. It must be remembered, however, that although the *original groups* contain large determinative errors, the *normal equations* constitute an accurate mathematical problem, and that the figures just given should be such that they satisfy the original equations of condition more nearly than any other possible set of values. This is equivalent to saying that if they be substituted in the 47 groups of Division I, Table 121, the sum total of the errors should be zero.

The formula actually used in Table 121 is not the formula just given, since for reasons to be explained later I have discarded the results of operating upon seven variables, and taken cognizance of only four elements. I have, however, made the trial of applying the above values to the groups in Division I

and find that the sum of the plus and minus errors is 29 pounds, being an average error of only one-half a pound to each group, which is very close to mathematical accuracy.

The true way of proving the correctness of values deduced from such a series of equations is first to eliminate in the order *G*, *F*, *E*, *D*, *C*, *B*, *A*, and then in the order *A*, *B*, *C*, *D*, *E*, *F*, *G*, to see if the two sets of answers agree; but as each such double solution, when every step of the work is proven to avoid error, consumes nearly two weeks of steady work, this reverse process has not been carried out in every one of the cases herein recorded. It has, however, been used to corroborate the following less tedious method of proof which is described for the benefit of future investigators.

The process of elimination is performed according to the following chart, where each figure represents an equation, and each bracket the combination of two equations by multiplication and subtraction.

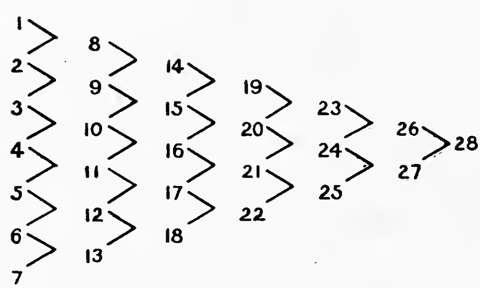

CHART SHOWING METHOD OF DETERMINING SEVEN UNKNOWN QUANTITIES IN SEVEN EQUATIONS.

After the determination of the final factor in equation No. 28, the value of each element is successively determined by substitution in Nos. 26, 23, 19, 14, 8, and 1. After the last unknown is thus found the values are substituted in No. 7, and if it is then found that the results agree to the seventh or even to the sixth logarithmic place, it may confidently be asserted that the values are correct to the third and sometimes to the fourth integer, and this is amply sufficient for the work in hand.

Notwithstanding such methods of proof and the reasonable,

although in some respects the unexpected, nature of the results just given from Division I, it is with no little disappointment that I am forced to confess that further investigation throws grave doubts on the validity of this method of least squares when applied to such a number of unknown quantities, and when any one of these quantities is of very little importance. The reasons for this conclusion will appear in the results shown in Table 122, which were obtained from the normal equations derived from the groups composing Division II.

TABLE 122.

Effect of Certain Elements upon the Strength of Steel as Determined from Division II in Table 121.

Order of solution.	Effect of .001 per cent.						Strength of pure iron.
	C.	Si.	Mn.	S.	P.	Cu.	
Forward . . .	+148.403	+36.030	+29.069	+367.923	—34.340	—29.110	42347
Backward . .	+148.402	+36.012	+29.056	+367.467	—34.203	—29.088	42530

NORMAL EQUATIONS FROM THE HIGH ACID OPEN-HEARTH HEATS, CONSTITUTING DIVISION II OF TABLE 121.

Equation from A; 3,008,187 A + 990,763 B + 5,453,335 C + 202,211 D + 351,674 E + 743,270 F + 650,950,560 G = 708,894,410.

Equation from B; 990,763 A + 441,605 B + 1,596,765 C + 57,835 D + 91,526 E + 207,280 F + 212,514,226 G = 230,460,700.

Equation from C; 5,453,335 A + 1,596,765 B + 10,427,125 C + 391,865 D + 704,040 E + 1,447,300 F +1,201,479,570 G = 1,298,675,100.

Equation from D; 202,211 A + 57,835 B + 391,865 C + 14,854 D + 26,895 E + 54,730 F + 44,851,610 G = 48,331,270.

Equation from E; 351,674 A + 91,526 B + 704,040 C + 26,895 D + 52,914 E + 102,250 F + 76,070,701 G = 84,275,880.

Equation from F; 743,270 A + 207,280 B + 1,447,300 C + 54,730 D + 102,250 E + 208,300 F + 162,236,870 G = 177,275,000.

Equation from G; 650,950,560 A + 212,514,226 B + 1,201,479,570 C + 44,851,610 D + 76,070,701 E + 162,236,870 F + 145,264,796,433 G = 154,504,087,640.

After laborious attempts to find any mathematical error, I am certain that the discrepancies between the results found by solving in reverse order are due solely to logarithmic errors, and could only be lessened by using logarithm tables of more than seven places. But these errors are of no importance, and it is certain that the values are approximately correct mathematically speaking, although they are absurd from a practical point of view.

If .001 per cent. of sulphur did actually cause an increase

of 367 pounds, then .06 per cent., which is a very common content, would increase the strength 22000 pounds, when in reality its effect is very slight, if it is even appreciable. Phosphorus is shown as a minus quantity, which is entirely wrong, and copper is given at — 29 pounds, which is equivalent to saying that one-half of one per cent. would reduce the strength 14,500 pounds, when, in fact, a content of even one per cent. does not seem to have any effect at all.

These ridiculous values place in question the validity of the method of least squares, by which they were determined, and the next section will attempt to survey the territory over which it has jurisdiction.

SEC. 157.—*Application of the method of least squares as limited by the conditions of the problem.*—The fundamental difficulty in the solution of Division II is the fact that the iron is not self-determining. The highest percentage of iron in any group of the division is 98.720, and the lowest is 97.884, being a ratio of less than 101 to 100. It is true that the ratios in Divisions I and III are very little higher than this, but in both these cases there is a determining condition in the fact that there are a number of groups which are nearly pure iron, and it will evidently be less probable that a wrong result will be found under such circumstances.

The only way, therefore, of obtaining an intelligent result for Division II is to make the iron self-determining, and since this can not be done within the limits of the division, it is necessary to combine it with Division I. This combination may be regarded as unjustifiable, since the effect of carbon decreases after a certain point is passed, but it can be answered that the curve in Figure XVIII gives no sign of falling, and that the value of carbon just found for Division II is greater than for Division I. Moreover, it will be shown in Table 123 that the value of carbon as found by the combination of I and II is higher than for I alone, so that there is good warrant for the union of the two.

This conjunction will tend to prevent an absurd result in the case of iron, and will give a better value for carbon; but it will not prevent a wrong estimation of an element like copper, which has very little influence upon the tensile strength. It is certain that the equations of condition are

not absolutely accurate, owing to the limitations of chemical research and the variations in the rolled test-bars. These errors are incorporated into the normal equations, and are distributed in the final solution so as to give the best mathematical result.

It does not follow that the values so found will accurately represent the actual practical state of affairs, for a purely fanciful result is not an unusual phenomenon in mathematics; thus, in the solution of every quadratic equation, two values are always produced by the plus and minus roots, and one of these values is often inapplicable to the original conditions. This occurred in the derivation of the curves given in Figure XVI, for there were two possible conic sections discovered in each case. One of them fitted the problem, while the other was a reverse curve exactly similar to the first, but situated for the most part in *minus* territory, and having an existence only as a mirage of the true solution.

To prevent such a purely mathematical answer to the present practical problem it is necessary to discard two sets of variables:

(1) Those which are known to have very little effect.

(2) Those which are present in very nearly constant proportion.

If an element has no effect, then it can not be self-determining, but may be forced to bear all the results of analytical errors. If it is present in nearly constant quantity, then the slight variations can have very little determining effect.

From one point of view these limitations beg the question, for it becomes necessary to know in a general way the influence of an element before its value can be quantitatively determined. The ultimate logical consequences of such a provision need not be discussed, for, in the problem under consideration, it is known that copper has scarcely any influence upon the tensile strength, and that the same is true of sulphur when present in ordinary proportions.

In the case of silicon there is a chance for greater hesitation, but it will be noticed that in only eight groups is the content of this metalloid above .20 per cent., while in only three other groups, or 11 in all, is it over .03 per cent.

Within the limits of .00 and .03 per cent., which thus includes five-sixths of the groups, the power of silicon is not enough to disturb the calculation.

SEC. 158.—*Effect of carbon, manganese, phosphorus, and iron upon the ultimate strength.*—Having thus decided to neglect the effect of silicon, sulphur, and copper, the equations of condition are simplified so that they take the following form:

EQUATIONS OF CONDITION.

From Group I; 82 A + 290 C + 34 E + 99434 G = 52090.
From Group II; 105 A + 380 C + 74 E + 99193 G = 57375.

From these may be deduced the following normal equations:

NORMAL EQUATIONS, DIVISION I.

Equation from A; 1,210,191 A + 4,298,830 C + 450,670 E + 710,516,809 G = 471,142,635.

Equation from C; 4,298,830 A + 15,861,200 C + 1,644,430 E + 2,581,030,930 G = 1,697,750,700.

Equation from E; 450,670 A + 1,644,430 C + 215,997 E + 300,954,795 G = 194,090,210.

Equation from G; 710,516,809 A + 2,581,030,930 C + 300,954,795 E + 460,910,659,759 G = 296,665,604,300.

NORMAL EQUATIONS, DIVISION II.

Equation from A; 3,008,187 A + 5,453,335 C + 351,674 E + 650,950,560 G = 708,894,410.

Equation from C; 5,453,335 A + 10,427,125 C + 704,040 E + 1,201,479,570 G = 1,298,675,100.

Equation from E; 351,674 A + 704,040 C + 52,914 E + 76,070,701 G = 84,275,880.

Equation from G; 650,950,560 A + 1,201,479,570 C + 76,070,701 E + 145,264,796,463 G = 154,504,087,640.

NORMAL EQUATIONS, DIVISION III.

Equation from A; 1,505,996 A + 4,700,050 C + 225,664 E + 954,850,000 G = 574,293,000.

Equation from C; 470,005 A + 1,723,710 C + 83,790 E + 340,994,800 G = 198,609,150.

Equation from E; 225,664 A + 837,900 C + 48,942 E + 169,769,400 G = 98,593,980.

Equation from G; 9,548,500 A + 34,099,480 C + 1,697,694 E + 7,382,138,000 G = 4,206,995,000.

NORMAL EQUATIONS, DIVISIONS I AND II COMBINED.

Equation from A; 4,218,378 A + 9,752,165 C + 802,344 E + 1,361,467,000 G = 1,180,037,000.

Equation from C; 9,752,165 A + 26,288,330 C + 2,348,470 E + 3,782,511,000 G = 2,996,426,000.

Equation from E; 802,344 A + 2,348,470 C + 268,911 E + 377,025,500 G = 278,366,090.

Equation from G; 13,614,670 A + 37,825,110 C + 3,770,255 E + 6,061,755,000 G = 4,511,697,000.

These equations, when solved, give the values shown in Table 123. In two cases the elimination has been performed in the order G, E, C, A, and has then been repeated "backward" in the order A, C, E, G. The comparison of results shows the degree of accuracy obtained. In the other two cases the work was not repeated in this manner, but the table gives two values of iron. These two determinations are the result of substitution in the extreme equations, as shown by the chart on page 296, and the almost perfect agreement of the two proves that the work is correct within the limits of logarithmic error.

TABLE 123.

Effect of Carbon, Manganese, and Phosphorus upon the Strength of Iron, as Determined from Table 121 by the Method of Least Squares.

NOTE.—All values are in pounds per square inch.

No. of division. (See Table 121.)	Order of solution.	Effect of .001 per cent.			Strength of pure iron.
		Carbon.	Manganese.	Phosphorus	
Division I.	Forward,	+141.4929	—3.086216	+109.3771	37139.65 37139.67
Division II.	Forward, Backward,	+166.8914 +166.8939	+3.921577 +3.928512	+ 97.28167 + 97.24250	23236.27 23231.43
Divisions I and II combined.	Forward, Backward,	+152.9212 +152.9203	—3.902156 —3.901182	+131.6955 +131.6965	34326.69 34326.22
Division III.	Forward,	+103.4560	+5.298315	+ 94.08509	38996.13 38996.14

The values are given for Division I in order that they may be compared with those found by combining Divisions I and II. They are given also for Division II separately, in order to corroborate what was said in Sections 156 and 157 on the worthlessness of any solution of this division by itself. The value of 23236 pounds for the strength of pure iron is absurd, and, of course, this renders worthless all the other factors, but the coincidence of the results when the equations were worked in opposite directions proves conclusively the accuracy of the work.

Moreover, I have applied these values to the separate groups of Division II, and the greatest discrepancy in any one group between the actual and the calculated strength is 6784 pounds, while the sum of the plus and minus errors is only 4.2 pounds, being an average error of only 0.28 pounds for each group.

This shows again, what has been insisted upon elsewhere, that perfectly correct mathematical results may be inapplicable to the practical conditions unless the factors are self-determining.

The values found by the combination of Divisions I and II, and the values given for Division III, are those which have been applied to the groups in Table 121 under the titles of Formulæ No. 1 and No. 2. The antepenultimate column gives the tensile strength as calculated from the formula, while the penultimate shows the error, or the difference between this calculated value and the result found by the testing machine.

The accuracy of the formulæ may be judged from the fact that the sum of the plus and minus quantities for the acid steels, comprising Divisions I and II, is 29 pounds, being an error of half a pound for each group. In the case of the basic steels the error is only five pounds, or only one-fifteenth of a pound for each group.

SEC. 159.—*Value of carbon and phosphorus when manganese is neglected.*—In the preceding section it has been shown that manganese is a plus quantity in basic steels, and a minus quantity in acid metal. These contradictory values may seem improbable, although they are by no means impossible. In order to get a little more light on the subject, I have arbitrarily divided the list of groups, given in Table 121, into two sets, and have determined the most probable values of carbon, manganese, and phosphorus, for each set. It would naturally be expected that the results from one-half the number of groups would be less valid and less uniform than from the complete list, but they may nevertheless be of use as corroborative evidence.

The method of dividing the list was to take the odd numbers for one set and the even numbers for the other. Inasmuch as the original arrangement is on the basis of carbon content alone, it will be evident that this insures a fair division without any chance of selection in aid of any preconceived theory. It would have been much better if a calculation could have been made on those groups showing low manganese, and those with high manganese, but as the low steels did not offer any examples of a high content of this element, and the high steels did not offer any examples of a low content, the result would have been of no value.

In the case of the acid steel a mistake was made in taking for this arbitrary division the original list of groups, which, of course, was made up before the determinations of carbon were made by combustion. On comparing the numbers on this original list with the new arrangement, it was found that the two sets of so-called "odd" and "even" numbers really embraced the following groups, as given in Table 121, after they had been renumbered:

Odd numbers: Groups 1, 2, 3, 8, 9, 10, 13, 15, 18, 22, 23, 25, 26, 27, 29, 31, 33, 36, 38, 41, 42, 43, 44, and 45.

Even numbers: Groups 4, 5, 6, 7, 11, 12, 14, 16, 17, 19, 20, 21, 24, 28, 30, 32, 34, 35, 37, 39, 40, 46, and 47.

Inasmuch as one arbitrary division seems to be as good as another, and as the calculation is very laborious, it was deemed unnecessary to repeat the work simply for the sake of uniformity, but this explanation is made for the sake of any mathematician who might wish to test the accuracy of the solution. In the case of the basic steel, the odd and even figures were taken as they stand in Table 121. The results are given in Table 124.

TABLE 124.

Values of Carbon, Manganese, Phosphorus, and Iron, obtained by Arbitrarily Dividing the List in Table 121 According to Odd and Even Numbers, and Solving Each Division by the Method of Least Squares.

Factor.	Kind of steel.	Value in pounds per sq. inch.		
		Odd.	Even.	Combined.
.01 per cent. of carbon	Acid, Basic,	+1554 +1069	+1502 + 992	+1529 +1035
.01 per cent. of manganese	Acid, Basic,	— 0.18 +20	— 107 + 85	— 39 + 53
.01 per cent. of phosphorus	Acid, Basic,	+1451 + 799	+1032 +1100	+1317 + 941
Pure iron	Acid, Basic,	30824 40303	40519 37749	34327 38996

It will be seen that in each case the "combined" value, which is the original value given in Table 121, is very close to an average of the odd and even. This is by no means a foregone conclusion, and would not follow if the factors were not self-determining to a great extent.

It will also be seen that there are variations in the values of each one of the factors, but that manganese shows the widest range. In the acid steel the figure for the even numbers is — 107, while in the odd numbers it is only a small fraction. The variations in phosphorus are very small when compared with this, while those of carbon are insignificant. The value of iron must necessarily change with the other elements, since it is less self-determining than carbon or phosphorus.

The great differences, found in the values of phosphorus in the odd and even subdivisions of the basic heats, are easily explained. An examination of the table will show that of the odd numbers there are only four groups showing more than .04 per cent. of phosphorus, and only three groups in the even numbers. There is therefore too little variation for the phosphorus to have an overpowering self-determining effect. The combined figures are subject to the same criticism, but the larger number of groups gives the results a greater validity.

Taking into consideration the fact that manganese is indicated as positive in basic and negative in acid steels, and that it gives wide differences in value between the odd and even lists, it would seem reasonable to suppose that it has very little effect at all when present in usual proportions, since the method of least squares should give a reliable result for an element which has a strong and positive action, when such an element is present in widely varying porportion.

Accepting such a conclusion, it remains to be seen whether a true formula can be deduced by omitting manganese altogether, and ascribing all the variations in tensile strength to the carbon, phosphorus, and iron. On this new basis the following normal equations are formed, the solutions of which are given in Table 125.

NORMAL EQUATIONS, OMITTING B, C, D, AND F.
DIVISIONS I AND II COMBINED.

Equation from A; 4,218,378 A + 802,344 E + 1,361,467,000 G = 1,180,037,000.
Equation from E; 802,344 A + 268,911 E + 377,025,500 G = 278,366,090.
Equation from G; 13,614,670 A + 3,770,255 E + 6,061,755,000 G = 4,511,697,000.

DIVISION III.

Equation from A; 1,505,996 A + 225,664 E + 954,850,000 G = 574,293,000.
Equation from E; 225,664 A + 48,942 E + 169,769,400 G = 98,593,980.
Equation from G; 9,548,500 A + 1,697,694 E + 7,382,138,000 G = 4,206,995,000.

The data in Table 125 may be expressed in simple formulæ, an allowance being made for the fact that there is never quite 100 per cent. of iron in any steel. In Table 126 these formulæ are applied to the groups of metals given in Table 121.

TABLE 125.

Effect of Carbon and Phosphorus upon the Strength of Iron.

NOTE.—All values are expressed in pounds per square inch.

Kind of steel.	Effect of .001 per cent.		Strength of pure iron.
	Carbon.	Phosphorus.	
Acid steel; Divs. I and II,	148.495	126.449	33212.2
Basic steel; Division III,	108.542	119.707	40196.5

In order to see whether these formulæ satisfy all the classes of steels under consideration, the results in Table 126 may be analyzed by the following method:

Silicon: Referring to the acid steels in Table 121, it will be found that there are eight groups containing .22 per cent. or over of silicon. Four of these, 49, 55, 56, and 60, show an error in Table 126 of less than 2000 pounds. There are two groups, 52 and 54, having an aggregate plus error of 6390 pounds, and two groups, 57 and 61, with an aggregate minus error of 7080 pounds. Thus there is no evidence that silicon influences the result.

Sulphur: There are six groups in the acid steels, 2, 10, 11, 17, 18, and 31, which contain .055 per cent. or more of sulphur, and none of these shows an error in Table 126 of over 2000 pounds. In the basic steels there are eight groups, 73, 77, 88, 91, 92, 98, 102, and 110, showing over .055 per cent., and the greatest error in any of them in Table 126 is 1680 pounds. Thus the sulphur does not seem to affect the situation.

Manganese: There are sixteen acid groups containing .75 per cent. or more of manganese. Of these there are six, 36, 39, 40, 43, 45, and 53, which have an error in Table 126 of less than 2000 pounds, while group 48 is only 60 pounds above this figure. Of the remainder there are five groups, 44, 47, 50, 51, and 62, giving an aggregate plus error of 19310 pounds, and four groups, 34, 42, 58, and 59, with an aggregate minus error of 13720 pounds. This would indicate, if it indicates anything,

that manganese has a minus value in the acid steels, which is in accordance with the mathematical deductions of the last section.

Table 126.

Ultimate Strength of the Steels Given in Table 121 as Compared with the Results Obtained from the Following Formulæ.

Formula for Acid Steel; 33,000+1485 C+1260 P = Ultimate Strength.
Formula for Basic Steel; 40,000+1085 C+1200 P = Ultimate Strength.

	Number of group.	Ultimate strength.			Number of group.	Ultimate strength.			Number of group.	Ultimate strength.		
		Actual.	Calculated from formula.	Diff. between actual and calculated strengths.		Actual.	Calculated from formula.	Diff. between actual and calculated strengths.		Actual.	Calculated from formula.	Diff. between actual and calculated strengths.
Acid steel.	1	52090	49460	—2630	22	59110	59200	+ 90	43	71170	72560	+1390
	2	57375	57920	+ 545	23	65020	67030	+2010	44	72320	75440	+3120
	3	57310	57500	+ 190	24	60690	58880	—1810	45	78020	78510	+ 490
	4	57430	59520	+2090	25	58820	58570	— 250	46	76830	81560	+4730
	5	57140	57470	+ 330	26	62940	63200	+ 260	47	76940	80300	+3360
	6	62870	61880	— 990	27	62890	63490	+ 600	48	82680	84740	+2060
	7	55450	54740	— 710	28	64880	65070	+ 190	49	87410	87620	+ 210
	8	58780	58770	— 10	29	63210	61890	—1320	50	86980	89310	+2330
	9	56830	54510	—2320	30	62650	61850	— 800	51	90750	95720	+4970
	10	60870	60560	— 310	31	64950	66510	+1560	52	92630	95200	+2570
	11	62610	61440	—1170	32	65180	64990	— 190	53	99300	99810	+ 510
	12	61190	59570	—1620	33	62850	62930	+ 80	54	97270	101090	+3820
	13	61430	62850	. 1420	34	71930	69010	—2920	55	102900	102200	— 700
	14	56990	54930	—2060	35	65100	63580	—1520	56	107300	107620	+ 320
	15	59110	59970	+ 860	36	65590	65260	— 330	57	111740	108310	—3430
	16	59350	58460	— 890	37	65280	66200	+ 920	58	121210	117640	—3570
	17	59260	60730	+1470	38	69970	69960	— 10	59	126800	122150	—4650
	18	60900	60100	— 800	39	71210	72180	+ 970	60	116980	115290	—1690
	19	59310	62010	+2700	40	71870	73680	+1810	61	122950	119300	—3650
	20	61020	58860	—2160	41	69750	70430	+ 680	62	123620	129150	+5530
	21	61130	60370	— 760	42	78700	76120	—2580	. .	. . . .	. . . .	. . . .
Basic steel.	63	46420	43790	—2630	88	53000	53180	+ 180	113	57030	58600	+1570
	64	47550	46080	—1470	89	52950	54220	+1270	114	57060	57270	+ 210
	65	47060	46270	— 790	90	53380	53130	— 250	115	60870	59260	—1610
	66	47610	48070	+ 460	91	53600	54310	+ 710	116	63480	61890	—1590
	67	49010	47920	—1090	92	54950	54420	— 530	117	58970	58040	— 930
	68	47130	46930	— 200	93	52910	53880	+ 970	118	60770	60200	— 570
	69	47570	47410	— 160	94	52980	54350	+1370	119	59110	59220	+ 110
	70	47010	47610	+ 600	95	54880	55150	+ 270	120	63400	60380	—3020
	71	47300	48540	+1240	96	52750	53560	+ 810	121	63740	61510	—2230
	72	48980	48530	— 450	97	57210	59050	+1840	122	60810	61290	+ 480
	73	49770	48730	—1040	98	56980	56760	— 220	123	63110	62650	— 460
	74	49250	51320	+2070	99	54860	55420	+ 560	124	60740	60960	+ 220
	75	48830	48870	+ 40	100	60580	59850	— 730	125	60870	61920	+1050
	76	49150	49590	+ 440	101	56680	56560	— 120	126	67570	65230	—2340
	77	50880	50410	— 470	102	58790	57880	— 910	127	66480	66260	— 220
	78	49090	50380	+1290	103	55090	56550	+1460	128	67480	64750	—2730
	79	49220	50710	+1490	104	54690	56850	+2160	129	66820	64590	—2230
	80	50910	49970	— 940	105	54890	55400	+ 510	130	63600	63330	— 270
	81	51060	51050	— 10	106	56870	57680	+ 810	131	63740	64940	+1200
	82	50900	51630	+ 730	107	59110	61140	+2030	132	63470	64650	+1180
	83	51140	53540	+2400	108	57010	57640	+ 630	133	67530	66500	—1030
	84	51200	51570	+ 370	109	59110	58830	— 280	134	67560	67800	+ 240
	85	51030	52370	+1340	110	60570	58890	—1680	135	68470	69890	+1420
	86	53020	54890	+1870	111	58860	58740	— 120	136	73010	76140	+3130
	87	800	55720	+ 920	112	58970	58980	+ 10	137	77950	78710	+ 760

Among the basic groups there are only two, 120 and 128, which contain more than .75 per cent. of manganese. These

two show an aggregate minus error in Table 126 of 5750 pounds. There are six other groups with a content of manganese between .65 and .75 per cent. Five of these, 90, 101, 109, 115, and 127, show an error under 2000 pounds, while the remaining group gives a minus error of 2340 pounds. There is, therefore, a slight indication that manganese strengthens basic steel, as was discovered in the last section.

Phosphorus: There are thirteen acid groups containing .08 per cent. of phosphorus or more, and seven of these, 6, 10, 11, 13, 17, 28, and 31, have an error in Table 126 of less than 2000 pounds. Of the remainder, four groups, 4, 19, 23, and 62, give an aggregate plus error of 12,330 pounds, and two groups, 58 and 59, give a minus error of 8220 pounds. This would indicate that the value of phosphorus in the acid steels is nearly correct but that it may be a trifle too high. The basic metals contain no examples of high phosphorus, and hence the value found can not be corroborated.

It will be found that these deductions must be materially modified on account of the investigations chronicled in Part III. In the later work the value of iron is nearly the same in acid and basic metal. This assuredly seems more in accord with reason, and gives greater force to the values found for the metalloids. The above calculation will be of interest to show how nearly an arbitrary equation can fit the case.

PART III.

EFFECT OF CARBON, MANGANESE, AND PHOSPHORUS UPON THE TENSILE STRENGTH OF IRON, AS DETERMINED BY SPECIAL MATHEMATICAL INVESTIGATIONS.

INTRODUCTORY NOTE.—A general synopsis of the argument and conclusions of both Parts II and III is given in Section 165.

SEC. 160.—*Values of carbon, manganese, phosphorus, and iron in a new series of acid steels.*—In the introductory note to Part II of this chapter it was stated that a second series of steels had been investigated. The method employed in the formation of the groups was the same as described in Section

155, and all the details of the work were performed by the same men that conducted the previous examination. The two series, which we may call the "old" and the "new," are therefore of equal force and virtue, and the testimony of one must always be considered in connection with the testimony of the other.

It was proven in Section 157 that the influence of silicon in small proportions was so slight that it did not make a satisfactory working factor for the method of least squares. The same was found true of sulphur and copper. In the plotting of the records of acid steel of the new series, however, it was found that the groups that contained high silicon seemed to show a greater tensile strength than steels of low silicon with the same content of carbon. As this was not the case in the old series, the groups were all put together in the former calculation, but in the light of this new evidence it would seem proper to separate them on the basis of their silicon content. This is easily done, since in both cases the high-silicon heats were put together in separate groups. In the low-silicon groups neither the total content nor the variations in this element seem sufficient to materially disturb the result.

The normal acid steels of the new series are shown in Division I of Table 128, and the normal acid steels of the old series in Division II. They are both combined to give the line *AA* in Figure XX.

The high-silicon steels of the new series are given in Division III, and those of the old series in Division IV. They are both combined to give the line *BB* in Figure XX.

The high-manganese and high-phosphorus steels of the old series are placed in Division V, but are not shown in the diagram.

Considering only the normal acid steels of both the old and the new series, as enumerated in Divisions I and II, a calculation was made by the method of least squares to find the values for carbon, manganese, phosphorus, and iron, which would most nearly satisfy the conditions of the problem. The results are shown in Table 127.

In the old series as originally formed, including the abnormal steels, the value of .01 per cent. of manganese was — 39 pounds. In the revised series, after omitting these groups, it

is — 23 pounds, while in the new series the value deduced is + 3. It would appear, therefore, that manganese does not make a satisfactory working factor in the calculations on acid steels, while the values obtained for it, in addition to being contradictory, show that it does not have a very important influence. In the following section, therefore, I have computed a formula from carbon, phosphorus, and iron alone, and have then compared the ultimate strengths as calculated from this formula with the actual tensile tests.

TABLE 127.

Values of Carbon, Manganese, Phosphorus, and Iron, as Determined by the Method of Least Squares from the Normal Acid Steels in Divisions I and II in Table 128.

Series.	Influence of .01 per cent. in pounds per sq. inch.			
	Carbon.	Manganese.	Phosphorus.	Iron.
New series, Division I	+1126	+ 3	+ 716	+4.0439
Old series, Division II	+1368	—23	+1068	+3.7544

SEC. 161.—*Values of carbon, phosphorus, and iron in acid steel when manganese is neglected, as determined from the normal steels of the old and the new series combined.*—Considering only the normal steels as given in Table 128, and omitting manganese from the problem, we shall have by the method of least squares the following equations, in which $A =$ the influence of .001 per cent. of carbon, expressed in pounds per square inch, $B =$ the influence of .001 per cent. of phosphorus, and $C =$ the influence of .001 per cent. of iron.

ACID STEELS;* DIVISIONS I AND II IN TABLE 128.

Equation from A; 3,227,256 A + 1,065,433 B + 1,676,848,333 C = 1,139,441,335.
Equation from B; 1,065,433 A + 488,892 B + 689,328,873 C = 441,177,250.
Equation from C; 1,676,848,333 A + 689,328,872 B + 1,043,135,334,268 C = 670,977,073,970.

The solution of these equations gives the following values:

	Lbs. per sq. in.
Effect of .001 per cent. of carbon	+ 121.6
Effect of .001 per cent. of phosphorus	+ 88.9
Strength of pure iron	38908

* The sum total of the coefficients in these equations is not quite 1,060,000,000,000, as it should be theoretically, because the factors in the old series relating to silicon, manganese, sulphur, and copper, have been omitted.

There is never quite 100 per cent. of iron in any steel, so that it would not be right to take the above determination of iron as a starting point. Theoretically it would be necessary to calculate the value of iron for each separate metal, and this was done in Table 121; but for practical purposes it will be assumed that structural steel contains 99.2 per cent. of iron, which by the above determination should confer a strength of 38600 pounds per square inch for acid metal.

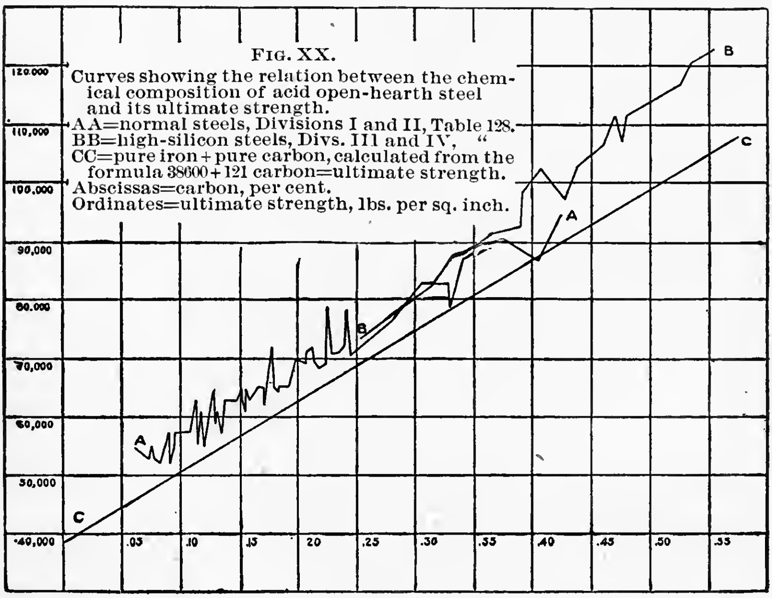

FIG. XX.—CURVES SHOWING RELATION BETWEEN THE CHEMICAL COMPOSITION OF ACID OPEN-HEARTH STEEL AND ITS ULTIMATE STRENGTH.

It then becomes practicable to write the following formula, by which the strength of acid steel may be calculated when the percentages of carbon and phosphorus are known, the answer being expressed in pounds per square inch.

Acid Steel; 38600 + 121 Carbon + 89 Phosphorus + R = Ultimate Strength.

The unit for carbon and phosphorus is .001 per cent. The factor *R* represents an allowance for the conditions under which the piece is rolled, whether finished hot or cold. In the present series of groups it is zero.

In Table 128 this formula has been applied to all the steels, both normal and abnormal, and the differences between the actual and the calculated ultimate strength have been placed in the last column. This difference will sometimes be spoken of as the "error" in subsequent remarks, as being the discrepancy between the recorded results and those obtained by calculation. An examination of this column reveals several notable points.

First: Group 54 is entirely abnormal. It is almost identical in composition with Group 53, and yet differs from it by 4200 pounds in strength. The fact that No. 53 is an average of twelve heats and conforms to the formula, while No. 54 is an average of only four heats, points to the latter as an erratic member which has some bar-sinister in its history. Out of numerous possibilities it is only necessary to mention that one of the test-bars might have been wrongly marked. This group will be neglected in the following observations.

Second: There is a decided difference between the old and the new series. The sum of all the plus values in Division I of Table 128, after omitting Group 54, is 49310 pounds, while the sum of the plus values in Division II is only 7290 pounds. The sum of the minus values in Division I is 10930 pounds, while in Division II it is 57780 pounds. The individual records corroborate these totals, for in Division I there are 39 groups where the error is plus, and only 16 groups where it is minus. On the other hand, Division II furnishes only 11 groups where the error is plus, while it has 38 groups where it is minus.

This seems too decided a record to be the result of chance, yet, as before stated, the two investigations relate to steels which were made in the same furnaces and handled by the same men, while the physical and chemical determinations were made on the same apparatus and by the same operators. In the light of this evidence it is not remarkable that results from different sources are sometimes inconsistent.

Third: There are seven groups among the normal acid steels where the actual strength is more than 2000 pounds *below* the calculated, and six of the seven, Nos. 29, 36, 45, 46, 49, and 50, show no striking peculiarity. The other group, No. 55, is low in phosphorus and sulphur, and rather high in manganese.

Table 128.

List of Groups of Acid Open-Hearth Steel of Old and New Series, Used in Determining the Effect of Certain Elements upon the Tensile Strength of Steel, Together with the Formula Obtained Therefrom by the Method of Least Squares.

Note.—All figures relating to ultimate strength are expressed in pounds per square inch.

Formula; the unit for carbon and phosphorus being .001 per cent., and the result being expressed in pounds per square inch.

38600+121 Carbon+89 Phosphorus=Ultimate Strength.

	No. of group.	No. of heats in group.	Composition; per cent.						Average ultimate strength of group.	Ultimate strength as calculated from formula.	Difference between actual and calculated ultimate strength.
			Carbon, by combustion.	Silicon.	Manganese.	Sulphur.	Phosphorus.	Copper.			
	1	5	.061	.007	.29	.071	.069	.34	54700	52120	—2580
	2	4	.073	.009	.24	.034	.050	.18	52850	51880	— 970
	3	7	.075	.005	.27	.054	.070	.21	54880	53910	— 970
	4	5	.076	.003	.31	.052	.080	.16	55190	54920	— 270
	5	6	.078	.006	.31	.036	.057	.22	53020	53110	+ 90
	6	7	.087	.008	.33	.043	.060	.15	55470	54470	—1000
	7	9	.090	.017	.33	.062	.088	.16	57310	57320	+ 10
	8	4	.091	.006	.31	.024	.035	.08	52180	52730	+ 550
	9	5	.091	.006	.36	.027	.059	.15	54760	54860	+ 100
	10	7	.095	.005	.39	.036	.051	.18	54960	54630	— 330
	11	8	.096	.011	.25	.060	.075	.22	57200	56890	— 310
	12	11	.103	.007	.35	.077	.074	.26	57260	57650	+ 390
	13	35	.106	.007	.35	.052	.070	.20	57140	57660	+ 520
	14	18	.116	.009	.29	.055	.070	.15	58860	58870	+ 10
	15	15	.116	.005	.32	.051	.075	.18	60770	59310	—1460
	16	9	.117	.007	.39	.028	.056	.08	56950	57740	+ 790
	17	14	.117	.006	.36	.057	.090	.11	58860	60770	+1910
	18	5	.119	.005	.38	.030	.041	.14	55030	56650	+1620
	19	11	.120	.006	.37	.080	.071	.24	58920	59440	+ 520
	20	12	.121	.008	.41	.026	.065	.06	58820	59030	+ 210
	21	11	.125	.007	.41	.032	.047	.08	56960	57910	+ 950
	22	15	.125	.016	.39	.080	.076	.24	61080	60490	— 590
Division I. Normal acid open-hearth steels. New series.	23	15	.126	.005	.48	.039	.063	.26	59060	59450	+ 390
	24	49	.127	.013	.39	.055	.075	.14	60850	60640	— 210
	25	11	.128	.006	.39	.057	.095	.13	61110	62540	+1430
	26	16	.130	.009	.40	.042	.053	.10	59170	59050	— 120
	27	69	.131	.007	.38	.051	.072	.18	58940	60860	+1920
	28	14	.132	.009	.47	.053	.076	.10	61260	61340	+ 80
	29	12	.134	.009	.44	.042	.058	.05	57080	59980	+2900
	30	14	.140	.007	.41	.074	.087	.20	62910	63280	+ 370
	31	10	.143	.006	.39	.065	.099	.14	62830	64710	+1880
	32	11	.148	.006	.49	.051	.071	.13	62860	62830	— 30
	33	16	.151	.003	.40	.045	.060	.21	60920	62210	+1290
	34	12	.151	.006	.33	.055	.084	.18	63030	64350	+1320
	35	12	.152	.007	.41	.029	.072	.13	62910	63400	+ 490
	36	16	.155	.012	.41	.034	.069	.09	60940	63500	+2560
	37	40	.155	.003	.41	.051	.073	.19	62910	63850	+ 940
	38	12	.159	.011	.40	.045	.056	.17	62930	62820	— 110
	39	8	.166	.007	.42	.048	.094	.18	65430	67050	+1620
	40	8	.170	.011	.46	.035	.070	.14	64640	65400	+ 760
	41	18	.170	.012	.43	.046	.074	.17	64840	65760	+ 920
	42	8	.171	.007	.41	.065	.078	.24	65260	66230	+ 970
	43	7	.180	.004	.53	.044	.072	.12	65320	66790	+1470
	44	9	.181	.008	.45	.049	.059	.19	64830	65750	+ 920
	45	10	.184	.009	.36	.051	.073	.22	64570	67360	+2790
	46	7	.207	.009	.41	.047	.088	.12	69410	71480	+2070
	47	5	.207	.011	.57	.042	.066	.14	69950	69520	— 430

TABLE 128.—Continued.

	No. of group.	No. of heats in group.	Composition; per cent.						Average ultimate strength of group.	Ultimate strength as calculated from formula.	Difference between actual and calculated ultimate strength.
			Carbon, by combustion.	Silicon.	Manganese.	Sulphur.	Phosphorus.	Copper.			
Division I.—Contin'd. Normal acid open-hearth steels. New series.	48	5	.214	.013	.47	.068	.077	.18	69700	71350	+1650
	49	7	.218	.009	.43	.049	.070	.17	68410	71210	+2800
	50	7	.224	.008	.37	.045	.079	.09	69440	72730	+3290
	51	5	.229	.011	.50	.032	.065	.07	70810	72090	+1280
	52	5	.244	.008	.46	.038	.044	.15	70360	72040	+1680
	53	12	.330	.035	.52	.029	.039	.05	82810	82000	— 810
	54	4	.331	.018	.51	.032	.039	.03	78610	82120	+3510
	55	11	.406	.060	.54	.030	.035	.07	86990	90840	+3850
	56	4	.424	.060	.57	.031	.043	.05	94470	93730	— 740
Division II. Normal acid open-hearth steels. Old series.	57	6	.082	.006	.29	.034	.034	.12	52090	51550	— 540
	58	12	.105	.009	.38	.059	.074	.18	57380	57890	+ 510
	59	11	.109	.008	.31	.036	.066	.14	57310	57660	+ 350
	60	12	.109	.007	.38	.048	.082	.15	57430	59090	+1660
	61	38	.113	.009	.43	.038	.061	.13	57140	57700	+ 560
	62	11	.113	.007	.48	.046	.096	.18	62870	60820	—2050
	63	5	.115	.007	.49	.029	.037	.09	55450	55810	+ 360
	64	18	.115	.013	.30	.043	.069	.17	58780	58660	— 120
	65	12	.116	.005	.59	.025	.034	.10	56830	55660	—1170
	66	19	.116	.015	.50	.069	.082	.19	60870	59930	— 940
	67	9	.116	.013	.47	.057	.089	.17	62610	60560	—2050
	68	18	.117	.018	.33	.039	.073	.20	61190	59250	—1940
	69	17	.117	.005	.45	.049	.099	.16	61430	61570	+ 140
	70	19	.118	.005	.59	.030	.035	.10	56990	55990	—1000
	71	72	.118	.007	.42	.045	.075	.14	59110	59550	+ 440
	72	13	.118	.008	.56	.044	.063	.14	59350	58490	— 860
	73	15	.118	.007	.45	.064	.081	.17	59260	60090	+ 830
	74	15	.118	.014	.57	.056	.076	.18	60900	59640	—1260
	75	21	.119	.009	.42	.051	.090	.14	59310	61010	+1700
	76	15	.119	.017	.43	.028	.065	.16	61020	58780	—2240
	77	96	.119	.009	.44	.043	.077	.16	61130	59850	—1280
	78	19	.123	.014	.44	.030	.063	.16	59110	59090	— 20
	79	6	.129	.008	.49	.050	.118	.16	65020	64710	— 310
	80	11	.131	.012	.47	.033	.051	.13	60390	58990	—1700
	81	13	.134	.015	.48	.035	.045	.15	58820	[illegible]	. . . .
	82	12	.138	.021	.36	.041	.077	.14	62940	62150	— 790
	83	38	.140	.016	.48	.042	.077	.18	62890	62390	— 500
	84	10	.143	.006	.39	.045	.086	.20	64880	63560	—1320
	85	10	.147	.012	.54	.024	.056	.16	63210	61370	—1840
	86	12	.151	.012	.64	.033	.051	.13	62650	61410	—1240
	87	7	.151	.005	.49	.055	.088	.16	64950	64700	— 250
	88	12	.156	.008	.57	.035	.070	.17	65180	63710	—1470
	89	8	.171	.011	.63	.026	.036	.10	62850	62500	— 350
	90	4	.178	.008	1.00	.043	.076	.14	71930	66900	—5030
	91	8	.183	.014	.68	.030	.027	.10	65100	63150	—1950
	92	9	.185	.008	.76	.028	.038	.13	65590	64370	—1220
	93	6	.193	.009	.67	.020	.036	.10	65280	65160	— 120
	94	5	.198	.013	.61	.032	.060	.14	69970	[illegible]	—2070
	95	8	.207	.012	.79	.045	.067	.15	71210	69610	—1600
	96	8	.212	.010	.82	.039	.073	.14	71870	70750	—1120
	97	4	.213	.012	.70	.019	.046	.14	69750	68470	—1280
	98	5	.225	.015	.99	.048	.077	.22	78700	72680	—6020
	99	5	.235	.016	.75	.027	.037	.14	71170	70330	— 840
	100	12	.240	.009	.76	.030	.054	.14	72320	72450	+ 130
	101	7	.242	.010	.86	.049	.076	.19	78020	74650	—3370
	102	6	.282	.009	.66	.033	.053	.16	76830	77440	+ 610
	103	6	.282	.010	.77	.023	.043	.14	76940	76550	— 390
	104	7	.306	.010	.79	.034	.050	.09	82680	80080	—2600
	105	11	.341	.020	.85	.034	.045	.11	86980	83870	—3110
	106	8	.374	.030	.83	.035	.057	.12	90750	88930	—1820

TABLE 128.—Continued.

	No. of group.	No. of heats in group.	Composition; per cent. Carbon, by combustion.	Silicon.	Manganese.	Sulphur.	Phosphorus.	Copper.	Average ultimate strength of group.	Ultimate strength as calculated from formula.	Difference between actual and calculated ultimate strength.
Division III. High-silicon acid open-hearth steels. New series.	107	14	.253	.150	.55	.026	.033	.03	73710	72150	— 1560
	108	7	.316	.200	.65	.025	.033	.06	82240	79770	— 2470
	109	7	.342	.190	.61	.020	.029	.04	87860	82560	— 5300
	110	7	.366	.170	.60	.022	.028	.04	91580	85380	— 6200
	111	9	.392	.210	.63	.022	.029	.06	98180	88610	— 9570
	112	9	.408	.230	.70	.021	.029	.04	102430	90550	—11880
	113	9	.461	.230	.64	.021	.029	.05	106560	96960	— 9600
	114	7	.470	.230	.65	.021	.031	.07	111830	98230	—13600
	115	7	.535	.200	.72	.022	.030	.07	120590	106010	—14580
Division IV. High-silicon acid open-hearth steels. Old series.	116	7	.333	.220	.65	.026	.041	.08	87410	82540	— 4870
	117	14	.390	.220	.68	.023	.034	.08	92630	88820	— 3810
	118	17	.428	.220	.65	.023	.036	.08	97270	93590	— 3680
	119	16	.438	.220	.69	.026	.033	.13	102900	94540	— 8360
	120	14	.477	.240	.69	.025	.030	.08	107300	98990	— 8310
	121	20	.480	.230	.69	.022	.032	.06	111740	99530	—12210
	122	10	.527	.250	.72	.027	.032	.07	116980	105220	—11760
	123	10	.554	.230	.68	.022	.032	.09	122950	108480	—14470
Div. V. High-manganese and high-phosphorus acid open-hearth steels. Old series.	124	13	.480	.090	1.12	.044	.106	.19	121210	106110	—15100
	125	18	.507	.061	1.19	.047	.110	.18	126800	109740	—17060
	126	9	.555	.090	1.13	.042	.109	.19	123620	115460	— 8160

On the other hand, there are ten groups where the actual strength is more than 2000 pounds *above* the calculated, and six of these, Nos. 90, 94, 98, 101, 104, and 105, show a high content of manganese. Of the others, No. 1 is low in manganese and high in sulphur, No. 62 is high in phosphorus, No. 67 is normal, and No. 76 is low in sulphur. Thus the only point that is gained by a review of those heats that display a difference of more than 2000 pounds between the calculated and actual strengths, is that high manganese seems to increase the tenacity. The figure 2000 pounds is chosen arbitrarily, since this seems a sufficiently close approximation to attain by any formula.

Fourth: The influence of manganese may be investigated by putting together the groups that show a similar content of this element. Thus there are twenty-nine groups that hold from .30 to .39 per cent. Nineteen of these have a plus error with a total of 21650 pounds, while ten groups have a minus error with a total of 8030 pounds. The difference between these totals, or rather their algebraic sum, is + 13620, which, divided by twenty-nine, gives the average error for one group.

Table 129 has been constructed by this process of differential synthesis for each increment of manganese, Group No. 54 being omitted for reasons given above.

TABLE 129.

Average Error of Groups in Table 128 Arranged According to their Manganese Content.

Manganese; per cent.		No. of heats.	Total minus error.	Total plus error.	Net error.	Average error.
Limits.	Average.					
.20 to .29	.27	6	— 5370	+ 10	— 5360	— 893
.30 to .39	.36	29	— 8030	+21650	+13620	+ 470
.40 to .49	.44	38	—10660	+27600	+16940	+ 446
.50 to .59	.55	13	—10520	+ 6600	— 3920	— 301
.60 to .69	.65	6	— 5730	+ 610	— 5120	— 853
.70 to .79	.76	7	— 7930	+ 130	— 7800	—1114
.80 to .89	.84	4	— 9420	. . . . . .	— 9420	—2355
.99 to 1.00	1.00	2	—11050	. . . . . .	—11050	—5525

It should be noted that most of the groups that contain high manganese are in Division II, and it has been remarked that there is some occult cause why the actual strengths of this division are slightly above the formula. The error arising from this condition is not sufficient to invalidate the records, but when most of the members of the division are slightly above the formula it is not extraordinary if the high-manganese groups follow the rule.

Passing over this reasoning, the table teaches that in steels containing about .25 per cent. of manganese, the actual ultimate strength is 893 pounds *greater* than would be indicated by the formula. With an increase in the content to .36 per cent. the actual strength is 470 pounds *less* than the formula, and with .44 per cent. it is 446 pounds *less*. From this point an increase in manganese gives an increase in strength.

It is important to notice that the figures + 446 for .44 per cent. of manganese, and + 470 for .36 per cent., are consistent with the minus values for the higher percentages, since manganese was entirely omitted in the derivation of the formula, and the result may therefore be looked upon as strictly applicable only to the average content of an element which it neglects; and if such an element does have an effect, it should make itself evident in a plus error on one side of the average and a minus error on the other.

This reasoning, however, is inconsistent with the fact that

manganese did not make a good working factor in the method of least squares. This inconsistency is explained by the values obtained in the first three lines of Table 129. With a content of .27 per cent., the actual strength is more than the calculated, and this is directly opposed to the law of higher strength with higher manganese. Moreover, the figure for .36 per cent. is practically the same as that for .44 per cent., being + 470 in one case and + 446 in the other. Considering the fact that three-quarters of all the groups were below .50 per cent. in manganese, and that the results on such metal were indecisive, it is not strange that manganese did not form a proper determinative member of the equations.

It is indicated, therefore, that with less than .50 per cent. of manganese the effect is not so uniformly marked as with larger proportions. Whether this is due to a different physical or molecular condition of soft metal, or to the presence of oxide of iron, or whether it arises from abnormality of the steels, or determinative errors in the records, can not be satisfactorily demonstrated.

The results, as a whole, justify the use of a formula for normal acid steels without any factor representing manganese. With contents above .60 per cent. of this element, it is necessary to make allowance for an increased strength, while above .80 per cent. the tenacity will rapidly increase.

It may also be necessary to allow for a very low content of manganese, since it was found in Table 129 that when there is less than .30 per cent. the actual strength was 893 pounds more than was indicated by the formula. This fact will be considered in Section 164 in connection with other information from the basic steels.

Fifth: The high-silicon steels all show a much greater strength than is given by the formula. The natural inference would be that silicon strengthens steel, but it is necessary to notice a curious and important fact, *viz.*, that the differences between the calculated and actual strength vary in proportion to the content of carbon, and not in proportion to the content of silicon.

In the new series, as given in Division III, the lowest carbon is .253 per cent., and the error is 1560 pounds. As the carbon increases to .316 per cent., the error rises to 2470

pounds, and with .342 per cent. it is 5300 pounds. The old series starts at .333 per cent. as the lowest carbon, and the error is 4870 pounds, so that the two series agree perfectly at the starting point. They also agree at their highest point, for the maximum carbon is .535 per cent. in the new series, and .554 in the old, the error being 14580 pounds in one case and 14470 in the other. Between these two extremes there are considerable variations, but in the main the law holds good that the error steadily rises with higher carbon.

A glance at the table will show that the content of silicon is practically constant throughout both series, and hence it is mathematically impossible to find any constant value for this element which will account for the variations in ultimate strength. In explanation of this it may be urged that the formula by which the strength is calculated gives a wrong value to carbon.

The answer to this criticism will be found in the line *CC* in Figure XX. The most casual inspection will show that this line is very nearly parallel to the trend of the line *AA*. It is impossible to decide exactly what that trend is, but the line *CC* seems to follow the average direction as near as it can be estimated. If any criticism were to be made, it would be that the tangent of *CC* was too great rather than too small. Bearing in mind that the carbon determines the tangent of these lines, and that the linear distance between them represents the effect of the other metalloids, it will be seen that the graphic delineation bears almost conclusive proof of the mathematical deductions.

The general trend of the line *BB* in Figure XX, which represents the high-silicon steels, forms a decidedly greater tangent to the horizontal axis than the line *AA* or its counterpart *CC*, and it would be impossible to draw a line which would be parallel to the trend of *BB*, and which at the same time would be parallel to the trend of *CC*, and since it has been remarked that the tangent of *CC* is fully as great as it can be to fall parallel to *AA*, and is possibly a step beyond, it will be evident that a different law is indicated for the metals with high silicon.

This law may be stated in two different ways:

First: That a constant percentage of silicon exerts a greater effect with each increment of carbon.

Second: That when a constant percentage of silicon is present, each increment of carbon exerts a greater influence.

It will be granted that this law has an upper limit, since the ultimate strength does not increase after a certain content of carbon is attained. It also appears that there is a lower limit, for, by referring again to Figure XX, it will be seen that the line *BB* joins *AA* at a point corresponding to about .25 per cent. of carbon, and it is therefore indicated that silicon has very little effect below this point, even when present in considerable proportions.

These high-silicon groups were all composed of heats made for steel castings, and it seems possible that the different conditions of casting temperature might exert an influence on the result. If this were true, it would also seem as if soft steel, made for castings, should show different physical properties from heats made in the ordinary way. Such does not seem to be the case, for Groups 9, 16, 20, 23, 85, 86, 89, 91, 92, 93, and 99, were composed almost entirely of casting heats, and yet conform very closely to the formula.

Sixth: The influence of sulphur has not been taken into account in the formula, and accordingly an investigation was made on the steels of Divisions I and II of Table 128 by the same process of synthetical differentiation that was used to discover the effect of manganese in Table 129, Group No. 54 being omitted as before. The results are given herewith, it being evident that no law is indicated.

16 groups	bet.	.019	and	.03	per cent.	sulphur	gave	an	average	error	of—485 lbs.
30	"	.03	"	.04	"	"	"	"	"	"	—260 "
27	"	.04	"	.05	"	"	"	"	"	"	—188 "
20	"	.05	"	.06	"	"	"	"	"	"	+319 "
7	"	.06	"	.07	"	"	"	"	"	"	+584 "
5	"	.07	"	.081	"	"	"	"	"	"	—378 "

Seventh: A similar table, which is given on the following page, shows the average error for the different percentages of phosphorus. As no regular law of error seems to exist, it seems as if the value which has been given to phosphorus must be approximately true.

All the foregoing conclusions are summarized in Section 165, in connection with the information derived from a similar study of basic steel.

1 group	bet.	.02	and	.03	per cent.	phosphorus	gave	an	av.	error	of—	1950	lbs.
11	"	.03	"	.04	"	"	"	"	"			— 117	"
8	"	.04	"	.05	"	"	"	"	"			— 159	"
16	"	.05	"	.06	"	"	"	"	"			— 324	"
16	"	.06	"	.07	"	"	"	"	"			— 268	"
34	"	.07	"	.08	"	"	"	"	"			— 173	"
11	"	.08	"	.09	"	"	"	"	"			+ 130	"
7	"	.09	"	.10	"	"	"	"	"			+ 947	"
1	"	.11	"	.12	"	"	"	"	"			— 310	"

SEC. 162.—*Values of carbon, manganese, phosphorus, and iron in a new series of basic steels.*—The steels considered in Sections 160 and 161 were all made by the acid process, but at the same time that they were under investigation, a similar series of basic steels was being studied. The groups were formed in the same way as described in Section 155, and a list of them is given in Division I of Table 131, while the old series of basic steels is shown in Division II. The numbers given to the groups are continuous with those in Table 128 to avoid confusion in references. The members of both series are combined to give Curve *AA* in Figure XXI.

The solution of the new series by the method of least squares is given in the first column of Table 130, while the

TABLE 130.

Values of Carbon, Manganese, Phosphorus, and Iron, as Determined by the Method of Least Squares from the Basic Steels in Divisions I and II of Table 131.

Series.	Influence of .01 per cent. in pounds per square inch.			
	Carbon.	Manganese.	Phosphorus.	Iron.
New series, Division I,	+ 935	+114	+939	+3.6335
Old series, Division II,	+1035	+ 53	+941	+3.8996

second column shows, for comparison, the determinations on the old series of basic steels as given in Table 121.

The results indicate that manganese has a decided strengthening effect upon basic steel, although it was found that in the case of acid steel no positive relation could be proven. This conclusion is corroborated by a calculation which was made by combining the old and new series, and solving the resultant equations by the method of least squares, without

taking any account of manganese as a factor. In the case of acid steel this process gave a satisfactory formula, but in the basic steel it gave the following results:

.01 per cent. of carbon = + 998 pounds.
.01 per cent. of phosphorus = + 1444 pounds.
Pure iron = 39987 pounds.

This value of phosphorus is not sustained by any other evidence. Referring to Table 130, it will be seen that the corresponding figure was + 939 for the new series, and + 941 for the old series. Thinking that there might be a clerical error, the solution was repeated in reverse order, as described on page 296, but the answers were found to be mathematically correct to five places.

This high value of phosphorus, when manganese is omitted, may be explained in the following way:

(1) It has been shown that carbon is self-determining in every series investigated, and that it gives fairly accurate results.

(2) The iron is less self-determining, but with basic metal, where some groups are so nearly pure iron, the chance for variations in this factor is less than in the case of acid steel.

(3) It is evident, therefore, that if manganese is a positive factor, and if it is neglected, its effect must be forced upon some other factor by the method of least squares, and phosphorus is the only factor available.

(4) The responsibility falls on phosphorus rather than on carbon, because the variations in phosphorus are very small, and it is therefore less self-determining than carbon, and less than in acid steel where it is present in large proportions.

Sec. 163.—*Values of carbon, manganese, phosphorus, and iron in basic steel, as determined from the old and the new series combined.*—Accepting as proven the conclusion of the foregoing section that manganese has a decided influence upon the tensile strength of basic steel, the groups of both the new and the old series, as given in Divisions I and II of Table 131, were combined, the resultant equations being given at the foot of page 323, in which A = the influence of .001 per cent. of carbon, B = the influence of .001 per cent. of manganese, C = the influence of .001 per cent. of phosphorus, and D = the influence of .001 per cent. of iron.

Table 131.

List of Groups of Basic Open-Hearth Steels of Old and New Series, used in Determining the Effect of Certain Elements upon the Tensile Strength of Steel, Together with the Formula obtained therefrom by the Method of Least Squares.

Note.—All figures relating to ultimate strength are expressed in pounds per square inch. The group numbers are made continuous with those of Table 128 to avoid confusion in references.

Formula: the unit for carbon, manganese, and phosphorus being .001 per cent., and the result being expressed in pounds per square inch.

37430+95 Carbon+8.5 Manganese+105 Phosphorus = Ultimate Strength.

	Number of group.	Number of heats in group.	Composition, per cent.						Average ultimate strength of group.	Ultimate strength as calculated from formula.	Difference between actual and calculated ultimate strength.
			Carbon, by combustion.	Silicon.	Manganese.	Sulphur.	Phosphorus.	Copper.			
	127	6	.051	.008	.25	.027	.008	.06	46630	45240	—1390
	128	13	.058	.007	.26	.036	.012	.10	48900	46410	—2490
	129	11	.062	.007	.38	.059	.019	.05	50640	48550	—2090
	130	10	.063	.017	.41	.046	.032	.06	50860	50260	— 600
	131	15	.069	.003	.39	.053	.013	.08	49030	48660	— 370
	132	6	.070	.006	.36	.050	.009	.08	47360	48090	+ 730
	133	7	.071	.008	.44	.038	.009	.08	47720	48860	+1140
	134	14	.071	.003	.50	.037	.012	.06	49060	49680	+ 620
	135	7	.072	.003	.34	.021	.008	.07	46670	48000	+1330
	136	42	.072	.005	.38	.037	.011	.08	48990	48660	— 330
	137	14	.074	.007	.38	.034	.021	.07	49280	49900	+ 620
	138	11	.079	.007	.33	.030	.007	.05	46950	48470	+1520
	139	17	.081	.006	.37	.035	.011	.08	47320	49420	+2100
	140	12	.081	.004	.42	.032	.007	.07	49070	49430	+ 360
	141	15	.082	.007	.38	.020	.011	.11	49150	49600	+ 450
	142	33	.082	.004	.43	.038	.014	.08	50770	50350	— 420
	143	13	.087	.006	.53	.036	.017	.10	51010	51980	+ 970
	144	12	.087	.006	.28	.030	.015	.08	51290	49650	—1640
	145	13	.101	.005	.40	.027	.007	.08	50710	51160	+ 450
	146	9	.102	.005	.37	.018	.010	.12	51090	51310	+ 220
	147	10	.105	.020	.53	.032	.012	.07	52970	53170	+ 200
Division I; new series.	148	8	.106	.019	.41	.036	.036	.06	53130	54760	+1630
	149	9	.118	.008	.41	.048	.014	.10	52990	53590	+ 600
	150	17	.119	.005	.36	.034	.015	.09	52930	53370	+ 440
	151	10	.125	.009	.38	.030	.008	.10	52750	53380	+ 630
	152	10	.127	.009	.43	.019	.010	.06	52980	54200	+1220
	153	8	.128	.006	.28	.035	.017	.07	53070	53760	+ 690
	154	12	.128	.012	.51	.035	.022	.08	54930	56230	+1300
	155	9	.131	.014	.41	.039	.033	.08	54870	56830	+1960
	156	13	.136	.003	.40	.040	.031	.09	57000	57000	+ . .
	157	12	.144	.004	.30	.037	.013	.10	55260	55030	— 230
	158	12	.147	.004	.38	.055	.019	.08	55100	56620	+1520
	159	24	.155	.006	.37	.034	.015	.08	55000	56870	+1870
	160	13	.162	.010	.30	.029	.017	.12	57060	57160	+ 100
	161	38	.164	.032	.38	.034	.015	.08	57020	57810	+ 790
	162	12	.165	.009	.41	.051	.021	.11	57220	58800	+1580
	163	9	.166	.007	.39	.032	.008	.07	55080	57360	+2280
	164	13	.169	.002	.51	.036	.018	.07	57070	59710	+2640
	165	13	.170	.008	.36	.019	.013	.09	55250	58000	+2750
	166	12	.170	.003	.36	.019	.012	.13	57210	57900	+ 690
	167	13	.170	.003	.42	.043	.040	.07	61070	61770	+ 700
	168	10	.175	.007	.41	.041	.029	.08	59060	60580	+1520
	169	11	.176	.009	.38	.052	.024	.10	58970	59900	+ 930
	170	10	.177	.008	.48	.034	.019	.08	59280	60320	+1040
	171	43	.179	.014	.38	.032	.014	.10	58970	59140	+ 170

TABLE 131.—Continued.

	Number of group.	Number of heats in group.	Composition; per cent. Carbon, by combustion.	Silicon.	Manganese.	Sulphur.	Phosphorus.	Copper.	Average ultimate strength of group.	Ultimate strength as calculated from formula.	Difference between actual and calculated ultimate strength.
	172	13	.183	.004	.36	.030	.008	.13	57350	58710	+1360
	173	13	.187	.004	.46	.054	.030	.07	60940	62250	+1310
	174	13	.188	.013	.30	.031	.015	.10	58900	59420	+ 520
	175	15	.192	.004	.39	.020	.013	.08	58900	60350	+1450
	176	13	.194	.004	.39	.019	.014	.09	60860	60640	— 220
	177	13	.194	.007	.51	.040	.023	.06	61340	62610	+1270
	178	8	.195	.004	.38	.024	.008	.08	59000	60020	+1020
	179	38	.202	.010	.42	.033	.016	.09	60740	61870	+1130
	180	10	.204	.006	.54	.039	.025	.11	63700	64020	+ 320
	181	15	.208	.005	.47	.038	.035	.07	63530	64860	+1330
	182	13	.209	.007	.47	.053	.024	.06	63220	63800	+ 580
	183	17	.214	.007	.42	.030	.008	.07	60860	62170	+1310
Division I, continued; new series.	184	38	.214	.004	.43	.031	.017	.11	63130	63200	+ 70
	185	7	.217	.009	.59	.039	.025	.07	68140	65680	—2460
	186	11	.219	.007	.32	.027	.016	.10	60790	62630	+1840
	187	12	.220	.006	.40	.018	.015	.08	63560	63300	— 260
	188	7	.229	.007	.49	.039	.043	.07	67770	67870	+ 100
	189	10	.233	.009	.47	.032	.007	.09	66330	64300	—2030
	190	9	.234	.007	.40	.030	.008	.08	63400	63900	+ 500
	191	10	.245	.009	.33	.028	.019	.13	63290	65500	+2210
	192	8	.248	.006	.40	.033	.018	.08	66220	66280	+ 60
	193	8	.252	.006	.50	.050	.026	.08	67090	68350	+1260
	194	20	.255	.010	.50	.035	.020	.10	67340	68000	+ 660
	195	10	.257	.007	.45	.019	.015	.08	66920	67250	+ 330
	196	5	.297	.007	.50	.037	.021	.07	71360	72100	+ 740
	197	6	.301	.005	.65	.029	.017	.08	76890	73340	—3550
	198	6	.025	.005	.04	.024	.009	.08	46420	41090	—5330
	199	4	.045	.006	.27	.045	.010	.11	47550	45050	—2500
	200	4	.050	.009	.33	.026	.007	.19	47060	45720	—1340
	201	4	.050	.005	.36	.031	.022	.15	47610	47550	— 60
	202	16	.052	.012	.35	.054	.019	.14	49010	47340	—1670
	203	6	.055	.015	.34	.019	.008	.10	47130	46380	— 750
	204	7	.055	.005	.22	.030	.012	.14	47570	45790	—1780
	205	12	.058	.005	.34	.029	.011	.14	47010	46980	— 30
	206	8	.061	.006	.46	.025	.016	.14	47300	48820	+1520
	207	18	.062	.008	.21	.036	.015	.12	48980	46680	—2300
	208	6	.065	.008	.36	.080	.014	.18	49770	48130	—1640
	209	17	.070	.013	.35	.034	.031	.14	49250	50310	+1060
	210	22	.074	.005	.36	.023	.007	.13	48830	48260	— 570
	211	19	.074	.009	.39	.018	.013	.10	49150	49140	— 10
	212	13	.076	.011	.41	.062	.018	.18	50880	50030	— 850
	213	94	.078	.003	.38	.031	.016	.11	49090	49750	+ 660
	214	15	.081	.005	.54	.031	.016	.13	49220	51400	+2180
	215	17	.083	.005	.42	.029	.008	.13	50910	49720	—1190
Division II; old series.	216	16	.083	.006	.57	.035	.017	.11	51060	51950	+ 890
	217	26	.084	.009	.25	.033	.021	.14	50900	49740	—1160
	218	23	.085	.014	.38	.032	.036	.14	51140	52520	+1380
	219	21	.090	.006	.40	.018	.015	.10	51200	50950	— 250
	220	121	.093	.006	.40	.032	.019	.13	51030	51660	+ 630
	221	17	.093	.006	.40	.038	.040	.16	53020	53860	+ 840
	222	21	.094	.011	.43	.036	.046	.18	54800	54840	+ 40
	223	14	.096	.007	.44	.065	.023	.16	53000	52700	— 300
	224	19	.099	.012	.28	.065	.029	.16	52950	52260	— 690
	225	14	.100	.009	.66	.029	.019	.15	53380	54540	+1160
	226	5	.102	.010	.47	.087	.027	.15	53600	53950	+ 350
	227	15	.103	.013	.44	.064	.027	.13	54950	53790	—1160
	228	15	.108	.008	.42	.019	.018	.11	52910	53150	+ 240
	229	125	.109	.010	.43	.031	.021	.12	52980	53640	+ 660
	230	103	.112	.005	.42	.034	.025	.16	54880	54260	— 620
	231	23	.115	.009	.43	.031	.009	.13	52750	52960	+ 210
	232	13	.117	.007	.46	.035	.053	.13	57210	58020	+ 810
	233	15	.118	.014	.49	.057	.033	.14	56980	56270	— 710
	234	18	.120	.004	.43	.018	.020	.12	54860	54590	— 270

TABLE 131.—Continued.

	Number of group.	Number of heats in group.	Composition, per cent. Carbon, by combustion.	Silicon.	Manganese.	Sulphur.	Phosphorus.	Copper.	Average ultimate strength of group.	Ultimate strength as calculated from formula.	Difference between actual and calculated ultimate strength.
	235	7	.121	.008	.54	.032	.056	.14	60580	59400	—1180
	236	11	.125	.012	.67	.038	.025	.13	56680	57620	+ 940
	237	10	.125	.019	.54	.060	.036	.11	58790	57680	—1110
	238	16	.126	.008	.62	.028	.024	.14	55090	57190	+2100
	239	19	.131	.008	.30	.029	.022	.13	54690	54730	+ 40
	240	20	.132	.006	.39	.027	.009	.13	54890	54230	— 660
	241	63	.132	.010	.47	.033	.028	.19	56870	56900	+ 30
	242	9	.134	.016	.51	.036	.055	.11	59110	60270	+1160
	243	15	.136	.009	.31	.029	.024	.13	57010	55500	—1510
	244	11	.137	.020	.72	.037	.033	.18	59110	60030	+ 920
	245	6	.142	.017	.53	.058	.029	.12	60570	58470	—2100
	246	10	.144	.008	.50	.020	.026	.12	58860	58090	— 770
	247	37	.144	.015	.52	.034	.028	.13	58970	58470	— 500
	248	14	.146	.015	.44	.019	.023	.11	57030	57460	+ 430
	249	21	.147	.005	.43	.027	.011	.10	57060	56200	— 860
	250	7	.151	.016	.68	.029	.024	.18	60870	60080	— 790
	251	9	.152	.008	.64	.034	.045	.17	63480	62040	—1440
	252	10	.153	.011	.46	.027	.012	.10	58970	57130	—1840
Division II, continued; old series.	253	13	.153	.008	.53	.034	.030	.16	60770	59620	—1150
	254	12	.155	.012	.39	.029	.020	.12	59110	57570	—1540
	255	6	.158	.012	.82	.032	.027	.17	63400	62250	—1150
	256	8	.164	.018	.57	.046	.031	.16	63740	61110	—2630
	257	7	.173	.009	.53	.021	.021	.11	60810	60570	— 240
	258	11	.180	.012	.56	.029	.026	.15	63110	62020	—1090
	259	10	.181	.006	.48	.031	.011	.10	60740	59860	— 880
	260	8	.181	.011	.37	.028	.019	.07	60870	59770	—1100
	261	5	.185	.039	.72	.049	.043	.11	67570	65640	—1930
	262	5	.190	.008	.72	.037	.047	.17	66480	66530	+ 50
	263	5	.196	.025	.86	.032	.029	.17	67480	66400	—1080
	264	10	.199	.012	.62	.030	.025	.12	66820	64230	—2590
	265	7	.204	.007	.45	.028	.010	.12	63600	61690	—1910
	266	8	.210	.010	.53	.020	.018	.13	63740	63770	+ 30
	267	6	.215	.005	.42	.024	.011	.16	63470	62580	— 890
	268	6	.231	.029	.36	.025	.012	.12	67530	63700	—3830
	269	5	.233	.008	.49	.020	.021	.13	67560	65940	—1620
	270	5	.260	.060	.31	.025	.014	.10	68470	66230	—2240
	271	5	.311	.080	.44	.029	.020	.07	73010	72820	— 190
	272	5	.338	.025	.62	.026	.017	.10	77950	76600	—1350

BASIC STEELS;* DIVISIONS I AND II, TABLE 131.

Equation from carbon; 3,503,736 A + 9,353,710 B + 423,710 C + 2,049,800,569 D = 1,230,544,020.

Equation from manganese; 9,353,710 A + 29,555,000 B + 1,350,180 C + 6,301,464,560 D = 3,660,255,100.

Equation from phosphorus; 423,710 A + 1,350,180 B + 74,634 C + 290,433,400 D = 169,202,400.

Equation from iron; 2,049,800,569 A + 6,301,464,560 B + 290,433,410 C + 1,439,974,511,304 D = 822,329,462,810.

The solution of these equations gives the following values:

	Lbs. per sq. in.
Effect of .001 per cent. of carbon	+ 94.9
Effect of .001 per cent. of manganese	+ 8.5
Effect of .001 per cent. of phosphorus	+ 105.4
Strength of pure iron	37733

* The sum total of the coefficients in these equations is not quite 1,460,000,000,000, as it should be theoretically, because the factors in the old series relating to silicon, sulphur, and copper, have been omitted.

Following the same line of argument as in acid steels, it is necessary to make allowance for the fact that there is never 100 per cent. of iron in any steel. The figure 99.2 per cent. was taken as a basis in Section 161, and it will also be taken in the present case. It is true that the phosphorus is generally lower in basic steel, but, on the other hand, the carbon is usually higher. On this assumption the strength given by the iron itself in an average basic steel will be 37430 pounds per square inch.

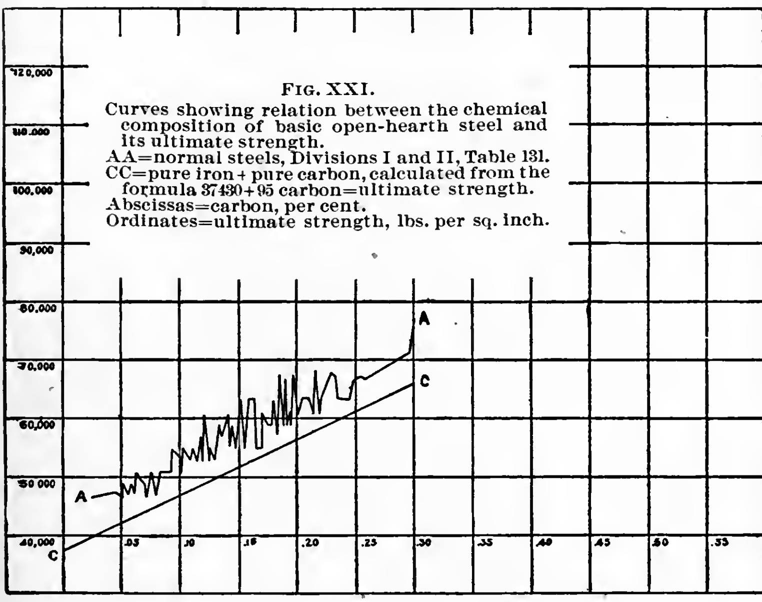

FIG. XXI.—CURVES SHOWING RELATION BETWEEN THE CHEMICAL COMPOSITION OF BASIC OPEN-HEARTH STEEL AND ITS ULTIMATE STRENGTH.

Constructing a formula in the same way as for acid metal, we have the following, the answer being expressed in pounds per square inch.

37430 + 95 Carbon + 8.5 Manganese + 105 Phosphorus + R = Ultimate Strength.

The factor R represents an allowance for the conditions under which the piece is rolled, whether finished hot or cold. In the present series of groups it is zero. In each case the unit is .001 per cent., but since manganese is seldom deter-

mined beyond two decimal points, it will be convenient in calculation to use a unit of .01 per cent. and a value of 85 pounds per unit, but it would be very confusing to so write the formula.

In Table 131 this formula has been applied to the basic steels of the old and the new series, and the differences between the actual and the calculated ultimate strengths have been placed in the last column. An inspection of these differences, or "errors," as they have been called, brings to light one or two points of interest.

First: The difference, which was found between the two series of normal acid steels, exists also between the two series of basic products. In Division I there are fifty-six groups that give a plus error, with a total of 57,130 pounds, while there are only fourteen groups that are minus, with a total of 18,080 pounds.

On the other hand, Division II offers only 24 groups having a plus error, with a total of 18,330 pounds, while it has 51 groups with a total minus error of 65,350 pounds. The net error of Division I is + 39,050 pounds, and that of Division II is — 47,020 pounds. The reason for this difference is unknown.

Second: An investigation was made into the effect of manganese in the same way as was done for acid steel in Table 129, and the results are shown in Table 132.

TABLE 132.

Average Error of Groups in Table 131, Arranged According to their Manganese Content.

Manganese; per cent.		Number of heats.	Total minus error.	Total plus error.	Net error.	Average error.
Limits.	Average.					
.20 to .29	.26	9	—13950	+ 690	—13260	—1473
.30 to .39	.36	47	—20190	+30680	+10490	+ 223
.40 to .49	.43	52	—16850	+24680	+ 7830	+ 151
.50 to .59	.53	24	—13230	+14240	+ 1010	+ 42
.60 to .69	.65	8	— 9720	+ 4200	— 5520	— 690
.70 to .79	.72	3	— 1930	+ 970	— 960	— 320
.80 to .89	.84	2	— 2230	....	— 2230	—1115

There is no such regular progression as was shown in the former case. This is readily explained by the fact that man-

ganese is given a value as part of the formula, and it is indicated that the value determined must be a very close approximation to the truth.

In the case of the steels containing between .20 and .29 per cent. manganese, the actual strength is 1473 pounds above the calculated. This will be again referred to in Section 164.

Third: The influence of sulphur was investigated in the same way as manganese. The results, given herewith, agree with those found from acid steel, in showing that sulphur exerts no regular influence upon the tensile strength.

13	groups	bet.	.01	and	.02	per cent. sulphur	gave	an	av.	error of	+ 317	lbs.
37	"	"	.02	"	.03	"	"	"	"	"	— 598	"
69	"	"	.03	"	.04	"	"	"	"	"	+ 251	"
9	"	"	.04	"	.05	"	"	"	"	"	— 397	"
12	"	"	.05	"	.06	"	"	"	"	"	+ 81	"
4	"	"	.06	"	.07	"	"	"	"	"	— 855	"
2	"	"	.08	"	.09	"	"	"	"	"	— 645	"

Fourth: A similar table, which is here given, shows the average error for the different percentages of phosphorus. This is done as corroborative evidence that the value of phosphorus in the formula is correct, for it may be assumed that if the value was too high or too low, the fact would be made manifest by a large error in the groups containing either high or low phosphorus. The fact that no regular relation exists seems to indicate that the deduced value is practically correct.

21	groups bet.	.00	and	.01	per cent. phosphorus	gave	an	av.	error of	— 20	lbs.
63	"	.01	"	.02	"	"	"	"	"	— 56	"
39	"	.02	"	.03	"	"	"	"	"	— 168	"
13	"	.03	"	.04	"	"	"	"	"	+ 261	"
7	"	.04	"	.05	"	"	"	"	"	— 234	"
3	"	.05	"	.06	"	"	"	"	"	+ 263	"

SEC. 164.—*Meaning of the term "pure iron."*—In the foregoing investigation, a slightly different value was found for "pure iron" as derived from acid steels, and "pure iron" as derived from basic metal. This contradiction is solely a matter of words. Absolutely pure iron never has been, and, in all probability, never will be made. The steels given in Table 120 are about as near to pure iron as can be found. Heat No. 4932 in that table contains .011 per cent. of phosphorus, .04 per cent. of manganese, .029 per cent. of sulphur, and .04 per cent. of copper. The carbon was not determined by combustion, but it must have been about the same as the average

sample of the six heats, which was .025 per cent. This would leave a total content of impurities of 00.145 per cent. If copper is omitted from the total, as having no appreciable effect, the total will be 00.105 per cent.

Notwithstanding this purity, the tensile strength of this heat is 46480 pounds, which is practically the same as the average of the group. The great strength of this metal, as compared with a steel containing a larger proportion of impurity, has already been discussed in Section 153, but must again be considered here.

It is easy to imagine that oxide of iron is present in this decarburized and dephosphorized product, and that it may confer an abnormal cohesive power. This supposition is corroborated by Tables 129 and 132, which indicate that both acid and basic steels, when low in manganese, are somewhat stronger than would be accounted for by their content of carbon and phosphorus, and it will be acknowledged that such steel holds a considerable quantity of oxygen.

It is true that these abnormal metals may contain unusual proportions of certain substances like hydrogen, nitrogen, or carbonic oxide, but since the effect of these constituents is entirely hypothetical, the most reasonable hypothesis is that oxide of iron increases the ultimate strength.

Whether this theory is perfectly true or not is of little importance so far as the present investigation is concerned, for the results obtained from absolutely pure iron would be utterly valueless as a guide in creating a proper formula. From one point of view there is no more real necessity of knowing the strength of pure iron than of knowing the strength of pure carbon or pure phosphorus. There may be no connection at all between the tensile strength of a carbide or phosphide of iron and the tensile strength of its separate components, since a chemical compound often has nothing in common with its parents.

In the foregoing pages, therefore, the term "pure iron" is arbitrary, and is intended to express simply the datum plane from which it is most convenient to start in order to find the strength of steel by a simple formula.

Sec. 165.—*Synopsis of the argument and conclusions in the foregoing investigations.*—The argument involved in the fore-

going calculations is so complicated, and the conclusions are so scattered throughout the text, that it will be convenient to give a general synopsis of Parts II and III of this chapter. As far as the conclusions are concerned, it is conceded that no one series of experiments can make a valid foundation for universal generalizations, but it has been deemed proper to put the discovered relations into the form of statements, which are to be accepted subject to the limitations of the premises.

Basis of the investigation.—The object of the investigation was to discover the influence upon the tensile strength of open-hearth steel, of the metalloids that are usually found therein. Both acid and basic metals were investigated, but the two kinds were kept separate throughout the work.

The preliminary tests of several hundred heats of each kind of steel were at hand, with a record of the ultimate strength of each, together with the content of sulphur, phosphorus, and manganese. These tests were made into several divisions on the basis of their ultimate strength, and these divisions were again subdivided so as to produce groups that would show high and low phosphorus, high and low sulphur, and high and low manganese. These groups were analyzed by taking an equal quantity of drillings from each bar, and determining the carbon by combustion, and also the silicon and the copper. The iron was calculated by difference.

Each one of these groups was then considered as a unit, and an equation was constructed from its chemical composition. On one side of the equation were the carbon, silicon, manganese, sulphur, phosphorus, copper and iron, and on the other side was the ultimate strength. The coefficients of the factors were the percentages found by analysis, while the factors themselves were the unknown quantities whose values were to be sought.

Mathematical calculations. — The only method which seemed to meet the case was the method of least squares, but the first application of this very complicated and laborious mathematical agent gave results which were palpably incorrect. It was demonstrated that the error arose from using silicon, sulphur, and copper as factors in the equations, when, as a matter of fact, they exerted no controlling influence.

Neglecting these elements, a solution was made by which values were found for carbon, manganese, phosphorus, and iron. Differences existed between the basic and acid steels in the values of all these factors, but the most striking variation was in manganese, it being found that it was a minus quantity in acid, and a plus quantity in basic steel.

After completing these calculations, the same line of work was repeated on an entirely new series of acid and basic steels. The results corroborated the former records in most respects, but the value of manganese was found to be very nearly zero in the case of the acid steel. Certain computations showed that this element gave very discordant results when the acid steels were separated into two arbitrary divisions, while the figures for the other metalloids preserved their general character, and the conclusions were drawn that manganese was an unsatisfactory factor in acid metal, that its effect upon the tensile strength was very small when present in ordinary proportions, and that a working formula could be constructed without it.

Finally the old and the new series of steels were put together and a solution was made of the combined list to find the most probable values of the metalloids. Manganese was neglected in the case of the acid steel, but it was found to have a decided influence upon basic metal.

From the values so determined, formulæ were constructed, and these were applied in Tables 128 and 131 to the groups from which they were derived. Against each group is placed the strength as given by the formula, as well as the difference between this figure and the actual strength.

This column of differences was then analyzed in the case of both acid and basic steels, and it was sought to find whether there was any law of error; for instance, whether high-sulphur groups would always give a plus difference and low-sulphur groups a minus difference, thus indicating that the formula did not fit the facts, and that the values were not correct.

From this series of steps the following conclusions were drawn:

Conclusions.—(1) The strength of pure iron, as far as it can be determined from the strength of steel, is about 38,000 or 39,000 pounds per square inch.

(2) An increase of .01 per cent. of carbon raises the tensile strength of acid steel about 1210 pounds per square inch, and of basic steel about 950 pounds. This difference between the effect of carbon upon acid and basic steels, as found by mathematical analysis, is corroborated by the graphic records in Figures XX and XXI.

(3) An increase of .01 per cent. of manganese has very little effect upon acid steel unless the content exceeds .60 per cent., but it raises the strength of basic steel about 85 pounds per square inch.

(4) An increase of .01 per cent. of phosphorus raises the tensile strength of acid steel about 890 pounds per square inch, and of basic steel about 1050 pounds.

(5) The following formulæ will give the ultimate strength of ordinary open-hearth steel in pounds per square inch, the carbon, manganese, and phosphorus being expressed in units of .001 per cent., and a value being assigned to *R* in accordance with the conditions of rolling and the thickness of the piece.

FORMULA FOR ACID STEEL.

38600 + 121 Carbon + 89 Phosphorus + R = Ultimate Strength.

FORMULA FOR BASIC STEEL.

37430 + 95 Carbon + 8.5 Manganese + 105 Phosphorus + R = Ultimate Strength.

(6) The metals, from which these data were derived, were ordinary structural steels ranging from .02 to .35 per cent. of carbon, and it is not expected that the formulæ are applicable to higher steels or to special alloys.

(7) A considerable difference may be found between steels which apparently are of the same composition, and which, as far as known, have been made under the same conditions.

(8) In the case of acid steel, an increase in manganese above .60 per cent. will raise the tensile strength above the amount indicated by the formula, the increment being quite marked when a content of .80 per cent. is exceeded.

(9) In steels containing from .30 to .50 per cent. of carbon, the value of the metalloids is fully as great as with lower steels, while the presence of silicon in such metal in proportions greater than .15 per cent. seems to enhance the strengthening effect of carbon.

(10) In steels containing less than .25 per cent. of carbon the effect of small proportions of silicon upon the ultimate strength is inappreciable.

(11) Sulphur, in ordinary proportions, exerts no appreciable influence upon the tensile strength.

(12) Both acid and basic steels containing less than .30 per cent. of manganese give an actual strength greater than is shown by the formula, and when this is taken in connection with the abnormal strength of the unusually pure metal shown in Group 198 of Table 131, it is indicated that oxide of iron raises the ultimate strength.

CHAPTER XVIII.

CLASSIFICATION OF STRUCTURAL STEELS.

SECTION 166.—*Influence of the method of manufacture on the properties of steel.*—The first problem in the writing of specifications for structural steel is the advisability of prescribing the method by which it shall be manufactured. Some engineers, with commendable fairness, hold that the way in which a bar or plate is made is a matter entirely beyond their dominion. Logically this position is impregnable, but it is not so practically, for although there is no essential difference in the results obtained from open-hearth and Bessemer steel in the ordinary testing machine, there is good testimony to show that the product of the converter is an inferior metal which gives way in a treacherous manner under shock.

It is granted that in a strict sense there is no such thing as treachery or mystery, but these are convenient terms to cover an undiscovered law. The evidence concerning the unreliability of Bessemer steel is made up for the most part of scattered individual opinions, many of which have been made on insufficient evidence, but they are too numerous to be entirely ignored, and they are fortified by the carefully considered statements of men whose words are weighed, and who are absolutely disinterested in their decisions. Thus A. E. Hunt, whose long experience as the chief of The Pittsburg Testing Laboratory gives much force to his opinion, writes as follows:* "Numerous cases have come under our observation of angles and plates which broke off short in punching, but although makers of Bessemer steel claim that this is just as

* *The Inspection of Materials of Construction in the United States. Journal I. and S. I.*, Vol. II, 1890, p. 316.

likely to occur in open-hearth metal, we have as yet never seen an instance of failure of this kind in open-hearth steel."

Mr. Hunt also quotes (*loc. cit.*) from a paper by Wailes before the British Association to the effect that "these mysterious failures occur in steel of one class, *viz.*, soft steel made by the Bessemer process."

There is also the testimony of W. H. White, Director of Naval Construction, Royal Navy.* "With converter steel, riveted samples have given less average strength, greater variations in strength, and much more irregularity in modes of fracture than similar samples of open-hearth steel. The basic open-hearth metal has proven to be as good as that made on the acid hearth, and, after full investigation, it will be used by the Admiralty in ship plates and boiler tubes on an equal footing."

My own experience leads me to think that Bessemer steel requires more work for the attainment of a proper structure than open-hearth metal, so that a thick bar is more apt to have a coarse crystalline fracture. This may be ascribed in any particular case to improper heat treatment, but if it is true that open-hearth metal would not be injured under a similar exposure, then it is proven that there is a difference between the metals, and, if this be acknowledged, then there is no necessity for further argument.

It is true that Bessemer metal has been used for rails, and that these are exposed to great stress and shock, but it is also true that a large number of rails break in service, and that the use of ordinary rail steel for bridges was long ago given up as dangerous. Moreover, it is quite probable that the number of broken rails would be considerably reduced if they were made of open-hearth steel.

It is acknowledged that the case is not yet closed, but until the foregoing statements are controverted by direct and positive evidence, the only safe way for the engineer is to prescribe that only open-hearth metal shall be used in all structures, like railroad bridges, where the metal is under constant shock, and where life and death are in the balance. In this connection it should be stated that the method by

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* *Experiments with Basic Steels. Journal I. and S. I.*, Vol. I, 1892, p. 35.

which the steel is made can not be discovered by ordinary chemical analysis. Certain experiments indicate that there is a difference between Bessemer and open-hearth steel in the character of the occluded gases, but this system of analysis is never resorted to in practice, and no provision is made for it in laboratories. Moreover, it is doubtful if any expert would risk his reputation by asserting positively, from any such evidence, that a certain steel was made by either one or the other process. Consequently, when open-hearth metal is specified, a careful watch should be kept in the steel works that there is no substitution of the inferior material.

SEC. 167.—*Chemical specifications.*—Another point concerning which there is room for discussion is the propriety of limiting the chemical composition. Some engineers contend that as long as the physical tests are fulfilled, the making of the metal is an entirely foreign matter. This position is untenable, for it would be possible to make a steel with 0.25 per cent. of phosphorus which would satisfy the ordinary tests of strength and ductility, and although such a content could usually be detected in the shops, a considerable proportion of the bars might be able to pass muster.

It is impossible to fix a limit of phosphorus below which there is no danger of treacherous breakage, but it is quite certain that, as the content is reduced, the danger of such disaster disappears. On this account it becomes not only the province but the duty of the engineer to specify the chemical composition of the metal that he buys.

In the construction of ordinary roof-trusses and similar work there is no necessity for stringency, and Bessemer steel with a maximum content of .10 per cent. of phosphorus may be allowed; but in railroad bridges, travelling cranes, and other structures where the steel is exposed to moving loads and continued shock, and where the consequence of failure may not be measured in money, the specifications should require the use of open-hearth steel with a maximum phosphorus of .06 per cent. The common limit at the present day is .08 per cent., but the time has come for another step in advance, since the difference in the cost of the purer metal has been reduced to an unimportant figure.

In addition to thus limiting the chemical content of phos-

phorus, it is necessary to specify the manner in which the sample shall be taken for analysis. There are four methods of doing this of which only one is correct, and this correct one is seldom or never used. Taking for illustration a rolled billet of steel three inches square, its cross-section may be mentally divided into nine equal squares, each having an area of one square inch. Eight of these squares are next to the surface, while only one is in the interior. This central square will include almost all the segregated portion of the mass.

Ordinarily a sample of such a billet would be taken by drilling to a depth of half an inch, but it is evident that this does not take cognizance of the interior core, and that the chemical determinations on the drillings will show too low a content of certain segregating metalloids.

Another method is to drill all the way to the center, and to take all the drillings that are made. Two-thirds of these drillings will come from the outside square and one-third from the inside, or a ratio of two from the outside and one from the interior, while the true ratio is eight to one; hence the content of segregating metalloids found by this method is higher than the true average.

A third method which is sometimes used, although manifestly inaccurate, is to take only those drillings that come from the central portion, but this will give a very much higher content of certain elements than will be found throughout the bar.

The fourth way is to plane the entire surface and thus get a true average, but, as before stated, this practice is seldom carried out.

In the case of angles, a very fair sample can be obtained by drilling into the bar as far as the center, the results so obtained being only slightly higher than the true values. In plates it is much more difficult to take a fair sample, since the segregated portion is in the body of the sheet, and it is usually impracticable to drill a hole without injuring the strength of the member.

It is easy to see that great injustice may be done by insisting on unusual methods of sampling. It would be perfectly right to state in the contract that drillings were to be taken

from the center of the plate, but it is not right to take them in this way in the absence of a previous understanding. On the other hand, the engineer has an indisputable right to investigate the homogeneity of any plate, and to reject those members that show excessive segregation.

It is necessary, therefore, to take some account of these variations, and in the following specification it is provided that when drillings are taken from the center of plates, the allowable maximum of phosphorus and sulphur shall be raised 25 per cent.; *e. g.*, from .04 to .05 per cent., or .08 to .10 per cent.

The engineer who has been calling for steel containing less than .08 per cent. of phosphorus, may deem it a step backward to allow the center of plates to contain .10 per cent., but it is necessary to consider that the new provision is merely a formal recognition of a fact, and that the higher phosphorus has always existed in the center of plates, particularly if they have been rolled directly from ordinary plate ingots which have not undergone a preliminary "roughing" and "cropping." It is also well to consider that less careful engineers, who have specified a maximum of .10 per cent. of phosphorus, have received many a plate that contained .12 per cent., and even .15 per cent., of this impurity. The fact of non-homogeneity in plates is a strong argument in favor of the further lowering of the allowable maximum, for, when all other conditions are the same, each decrease in the average content diminishes the increment due to segregation.

Some engineers may wish to specify that basic metal shall show a still lower phosphorus. There does not seem to be any proof that basic open-hearth steel of a given composition is more unreliable than acid metal of the same character, but in order to meet any possible danger, and because the cost of a little extra purification is not excessive, it is not amiss to require that the best basic steel shall not show over .04 per cent. of phosphorus.

The other elements need not be rigidly limited, for many combinations are possible, and some discretion should be left to the maker in the attainment of definite results. It is not uncommon for engineers of limited knowledge to write specifications that give an upper limit for every element, and

require a tensile strength which can not be obtained by the formula. The carbon should always be left open, so that if the maker wishes to reduce the phosphorus he may use carbon to get strength.

Manganese may be limited to .60 per cent. on the steels under 64000 pounds per square inch, and to .80 per cent. on harder metal. This will ensure a safe material, and will not be a burden on the manufacturer. Silicon is of little importance, but the maximum may be placed at .04 per cent. for soft steel, this proportion being seldom, if ever, exceeded.

Sulphur, in most cases, concerns the manufacturer more than the engineer, for if it is too high the bar will crack in rolling and be imperfect, while it seems to have no marked effect on the ductility of the finished piece. In material for eye-bars, however, there is danger that high sulphur may cause coarse crystallization during the heating necessary to form the eye.

Copper may be entirely neglected, for no ill effect upon the cold properties of low steel has ever been traced to its action, while thousands of tons of excellent metal have been made with a content of .75 per cent.

Rivet steel, like eye-bar flats. stands on an entirely different footing from other structural metal, for this must be heated and worked after leaving the manufactory. Only the very best of material should be used, and it should be so soft that it will not be injured by cold working or crystallized by overheating. The phosphorus should not be over .04 per cent., the sulphur not over .05 per cent., and the tensile strength not over 56000 pounds per square inch. These limits should be insisted upon whether acid or basic open-hearth metal be used.

Sec. 168.—*Use of soft steel in structural work.*—It is not the intention of this chapter to arbitrarily state just what should or should not be given as the best tensile strength for every purpose, but it is my opinion that a softer metal should be used for bridges than is often employed, because, although a slight sacrifice is made in the ultimate strength, there is a gain in the working strength due to the higher elastic ratio, and a decided increase in toughness and resistance to shock, so that the calculations may be made on the same basis for the working load as with a harder metal.

The fact that the elastic ratio rises as the ultimate strength decreases is not generally recognized, but will be shown in Table 133. This is constructed by comparing the groups of angles in Table 69, which are made by the same process, and are of the same thickness, and which contain the same percentage of phosphorus. It will be found that in every case the stronger steel gives a lower elastic ratio.

TABLE 133.

Rise in Elastic Ratio with Decrease in Ultimate Strength. Comparison of the Angles Given in Table 69 which are Made by the Same Process, of the Same Thickness, and with the Same Content of Phosphorus.

Kind of steel.	Content of phosphorus; per cent.	Thickness of angle, in inches.	Harder steels.			Softer steels.			Rise in elastic ratio in softer steels; per cent.
			Av. ultimate strength; pounds per square inch.	Average elastic limit; pounds per square inch.	Average elastic ratio; per cent.	Av. ultimate strength; pounds per square inch.	Average elastic limit; pounds per square inch.	Average elastic ratio; per cent.	
Basic O. H.	below .04	$\frac{5}{16}$ to $\frac{3}{8}$	58865	39692	67.43	52533	36284	69.07	1.64
		$\frac{7}{16}$ to $\frac{1}{2}$	58538	37827	64.62	53171	34891	65.62	1.00
		$\frac{9}{16}$ to $\frac{5}{8}$	59235	37487	63.28	51903	34026	65.56	2.28
		$\frac{11}{16}$ to $\frac{7}{8}$	59125	36035	60.95	51923	32356	62.31	1.36
Acid O. H.	.05 to .07	$\frac{5}{16}$ to $\frac{3}{8}$	65656	43713	66.58	60845	40891	67.21	0.63
		$\frac{7}{16}$ to $\frac{1}{2}$	65631	42191	64.28	60695	39415	64.94	0.66
Acid O. H.	.07 to .10	$\frac{5}{16}$ to $\frac{3}{8}$	66365	44486	67.03	60064	41143	68.50	1.47
		$\frac{7}{16}$ to $\frac{1}{2}$	65777	42817	65.09	60583	40170	66.30	1.21
Acid Bess.	.07 to .10	$\frac{5}{16}$ to $\frac{3}{8}$	66277	46422	70.04	60659	43417	71.58	1.54
		$\frac{7}{16}$ to $\frac{1}{2}$	65940	45280	68.66	59882	42518	71.00	2.34

The tendency in the first epoch of steel structures was toward a hard alloy, but the later practice has been a continual progress toward toughness. There was a halt in this movement at a tensile strength of 60,000 pounds, not entirely on account of any magic virtue in the figure, but because the ordinary mild steels gave that result, and a much higher price was charged for a softer metal. The conditions to-day are somewhat different, for the reduced cost of low-phosphorus pig-iron, and the introduction of the basic hearth, have altered the economic situation.

A steel with a tensile strength of 50,000 to 58,000 pounds per square inch is a most attractive material, possessing all

the good characteristics of wrought-iron with greater strength and toughness, and it seems probable that it will be extensively used in the future.

With this recommendation for the adoption of softer metal, certain classes are proposed from which the engineer can choose. In some cases the option is given between acid and basic open-hearth steel, but it must not be forgotten that it costs more to make low-phosphorus metal by the acid than by the basic process, so that the terms of the specification should be enforced after the contract is awarded, out of justice to the other bidders who have based their calculations on the letter of the law. In steel above .08 per cent. of phosphorus, this difference in cost disappears and there is no economy in the use of the basic hearth.

The option is sometimes given between open-hearth and Bessemer metal, but it will be understood that whenever the former is specified the latter is not admissible, although as a matter of course the manufacturer may supply open-hearth in place of Bessemer, if for any reason he wishes to use the better and more expensive material.

SEC. 169.—*Tests on plates.*—In the specifications for plates it will be noticed that a variation of 10,000 pounds per square inch is allowed, and that concessions are made for thick and wide sections. All this may seem to some engineers to be a step backward, but in reality these provisions have been in force for many years. The engineer who writes a new specification calling for a better elongation, never knows that he receives exactly the same steel that has been made before. The plate rollers have been driven to expedients which are not dishonest, but which are dangerously near the line of deception. Thus, if it is required that a test must be cut from one plate out of every ten, the manufacturer will leave a coupon on every plate and test strips which are cut from immediately next to them; after finding which plates fill the requirements, the coupons are cut from the others and the inspector is told that the pile is ready for him.

If every plate is to be tested, then a coupon is left upon each corner and a contiguous strip is privately tested by the maker. After finding which corner gives the best results, the other coupons are cut off and the plate submitted to the

inspector. This is not dishonest, for any one corner represents the plate just as much as any other corner, and it would manifestly be absurd to designate from which corner the test is to be taken.

It is also quite certain that no one corner represents the center of the plate, for the edges are always finished colder than the center, and it is just as certain that in a plate rolled direct from an ingot with only the usual amount of scrap, the corners in no way represent the part of the plate which corresponds to the segregated portion of the ingot.

It is by care in the preliminary testing rather than by improvement in the quality of material that advances have been made, and it is time that the fact be made known to engineers. The mill managers have been aided by the inspectors for most of these men (to their credit be it said) are anxious to pass material which they know to be good. They allow the manufacturer to put part of a heat into thick plates and part into thin, and make the tests on the three-eighths or one-half inch gauges; they pass over the sheets that are 100 inches wide, and cut the coupons from plates that are less than 70 inches. These concessions have been tacitly made in the past; I have merely put them into print.

On the other hand, I have called for higher tests on plates under 42 inches wide. This is because they can be made on a universal mill, and since better results can be had in this way, it is right to demand what there is a perfectly simple way of obtaining.

It will be seen that no allowance is made for a variation in tensile strength for different shapes, while concessions are made for differences in thickness. This inconsistency arises from the fact that it is generally known beforehand whether a certain heat of steel is to be rolled into angles, or plates, or eye-bars, and it is seldom that it is necessary to put part of a heat into one shape and part into another. On the other hand, it is almost always necessary to roll a charge into more than one thickness and more than one size of angles, plates, etc., and it is evidently an onerous restriction if proper allowance be not made for the normal variations due to different thickness.

SEC. 170.—*Standard size of test-pieces.*—In all the tensile tests

a length of eight inches is taken as the standard for all sections, allowance being made for variations in shape and size. It should be noted that this may soon be an obsolete method. Within the last few years there have been conferences held in foreign lands to establish uniform methods of testing, and it has been officially recommended that in the case of rounds the length of the test-piece shall be proportional to the square root of the sectional area. In Appendix V to the Report of the Committee on Standard Tests of the American Society of Mechanical Engineers, published in 1893, the formula is given $l = 12.0\sqrt{f}$ when $l =$ the length in inches and $f =$ the sectional area in square inches. In Table 134 I have calculated from this formula the proper length for rounds from one-half inch to $1\frac{1}{4}$ inches in diameter. It will be seen that the length is greatly reduced as the diameter grows less, and this, of course, is equivalent to demanding less elongation, while on larger sizes the length is increased, this being the same thing as demanding more elongation.

TABLE 134.

Calculation of $12.0\sqrt{f}$ for Different Diameters, together with the Proportional Elongation for the Given Lengths as Determined by Curve AA in Figure XV.

Diameter, in inches.	f, or area in square inches.	$\sqrt{f}$	$12.0\sqrt{f}$ = length in inches of test-piece.	Per cent. of elongation for lengths in preceding column; from Curve AA, Fig. XV.
½	.1963	.443	5.32	33.2
⅝	.3067	.554	6.65	31.5
¾	.4417	.665	7.98	30.2
⅞	.6013	.775	9.30	29.3
1	.7854	.886	10.63	28.7
1⅛	.9940	.997	11.96	27.8
1¼	1.2271	1.108	13.30	27.1

It is rather difficult to compare this system, in which the elongation is constant and the length varies, with the system wherein the length is constant and the required elongation varies; but an attempt is made to do this by obtaining the proportional elongation for the different lengths from Curve *AA* in Figure XV. The results are given in the last column of the table, and it will be found that the allowances for

changes in sectional area, given in the following pages, are in line with the system proposed by the International Committee.

I have not accepted the recommendations of the conference because the matter is in the hands of a committee of the American Society of Mechanical Engineers, and until this committee has made its final report, and until this has been officially accepted by the Engineering Societies of America, it would seem forward to attempt the inauguration of an entirely new system. A long time has been spent in arriving at the general adoption of an international standard length of eight inches, and it seems unfortunate from one point of view that a complicated change is to be proposed. If, however, such a revolution is consummated, it will be found that the system herein presented will not need to be destroyed but only translated.

It is understood in these specifications, as well as throughout this book, that the elastic limit is determined by the drop of the beam, for this is the universal method in American steel works and rolling mills. I have no sympathy with that group of agitators who are trying to introduce new meanings to old terms, and to apply old terms to new factors. It matters not whether the drop of the beam does or does not mark the spot where the elongation ceases to be exactly proportionate to the load. It is certain that it represents a critical point of failure, and this is acknowledged by the agitators before mentioned, who recommend its determination on all tensile test-pieces.

Moreover, it is shown in Section 141 that this is a definite point which can be determined more accurately than the reduction of area, and nearly as accurately as the elongation. If a new point is desired, such as is shown by an autographic device, then this new point should be given a new name. The term "elastic limit" has been preëmpted by general use, as part of a system of trade nomenclature, to designate the point where the beam drops.

Upon this determination all specifications and contracts are based, and any attempt to ascertain the elastic limit in any other way is a change in the contract requirements which would not be sustained in a court of equity. All calculations upon factors of safety in existing bridges are based upon this

"drop of the beam," and there seems to be no good reason why one arbitrary point should be substituted for another, and no reason why future work should not be carried on under the present established and well-understood system.

SEC. 171.—*General provisions on methods of testing.*—(1) Rivet rods and other rounds are to be tested in the form in which they leave the rolls, without machining.

Note.—This is apparently opposed to the recommendations of the International Conferences,* wherein it is proposed that round test-pieces shall be turned to one of four standard diameters, with shoulders and screw grip thread at each end, but it is stated elsewhere in the reports of the committee that only pieces for scientific investigation are to be prepared in this manner.

(2) Test-pieces from angles, plates, shapes, etc., shall be rectangular in shape, with a cross-sectional area of about one-half square inch, and shall be taken so that only two sides are machine finished, the other two having the surface which was in contact with the rolls in the last pass.

Note.—The report of the committee above mentioned recommends this method of cutting tests, but specifies that there shall be shoulders at each end. This necessitates considerable extra machine work without any notable effect upon the result. The limitation of the area of the piece prevents the passing of inferior material by an unusual increase in width.

(3) Should fracture occur outside of the middle third of the gauge length, the test is to be discarded as worthless if it falls below the standard.

Note.—This provision is copied from the report of the above committee, and is much to be commended. A deficient elongation when the piece breaks near the end is not the fault of the material, but a mere accident. On eye-bars, a failure in the eye should condemn the method of forming the head rather than the quality of the steel.

(4) In case one test-piece falls slightly below the requirements in any particular, the inspector shall allow the retesting of the lot or heat by taking four additional tests from the same lot or heat, and if the average of the five shall show that the steel is within the requirements, the metal shall be accepted.

* *Report of Committee on Standard Tests to the Am. Soc. Mech. Eng.*, Appendix V.

(5) Drillings for chemical analysis may be taken either from the preliminary test-piece or from the finished material, but if the sample be taken from the center of a sheared or universal-mill plate, the maximum limit of both phosphorus and sulphur shall be raised 25 per cent.; *e. g.*, from .04 to .05 per cent., or .08 to .10 per cent.

(6) The pulling speed of the machine for breaking test-pieces shall not be less than one-quarter inch per minute, nor more than three inches per minute.

(7) The elastic limit shall be determined by the dropping of the beam.

SEC. 172.—*Classes of steel proposed.*—The following specifications do not deal with metal for special purposes, like gun carriages, armor plate, etc., but are intended to cover more or less fully the needs of the structural engineer. I do not expect that they will ever be adopted in their entirety as standard requirements, but this seems to be the simplest form in which to condense the investigations that have been recorded in the foregoing chapters, and to present the variations in the physical properties caused by changes in the history and section of the test-piece.

Engineers who do not wish to cumber their specifications with so many allowances for thickness and section, will find herein the reason for many troublesome questions arising in the testing of the material, for I have tried to tabulate, as fairly as can be estimated, the effect of conditions that are ruled more by the laws of nature than by the skill of the manufacturer.

At the same time it will be found that the matter is not as complicated as would be indicated at first sight, for one page of general provisions and one page of physical limits for each kind of steel can hardly be called a very voluminous document to cover the specifications upon structural shapes.

The engineer who will compare the proposed requirements with what is demanded in other countries, will find a remarkable difference. The specifications which are in general use in Germany are as follows:*

* *Normalbedingungen für die Lieferung von Eisenconstruktionen für Brücken- und Hochbau*, Otto Meissner, 1893; also, *Ueber die Arbeiten der Flusseisen-Commission*, F. Kintzlé, 1892.

For Rivets.—Ultimate strength from 51200 to 59700 pounds per square inch; elongation 22 per cent. in eight inches.

For other structural material.—Lengthwise tests: Ultimate strength from 52600 to 62600 pounds per square inch; elongation 20 per cent. in eight inches.

Crosswise tests: Ultimate strength from 51200 to 64000 pounds per square inch; elongation 17 per cent. in eight inches.

These are given as the limits accepted by the leading engineering societies of that country, and I am informed by Mr. Kintzlé* that they represent the general requirements at the present time for all classes of material. It is safe to say that if American engineers were satisfied with the German standards, there would not be one rejection for deficient ductility where there are twenty under our more rigid requirements; and if they would be content with a steel having an ultimate strength between 52000 and 62000 pounds per square inch, there would not be one-fifth the number of heats discarded for being outside of the tensile limits. The bearing of these facts upon the cost of the material is self-evident.

I do not advocate any sacrifice of strength to economy, but I would impress upon American engineers that this soft metal is eminently suitable for structural work, while by maintaining their present chemical limitations and their requirements concerning ductility, they will be assured of a material which is equal in quality to any produced in the world.

Class I.

Extra Dead Soft; for Common Rivets, Wire Cables, and other Purposes where Exceptional Toughness is Required.

Method of manufacture.—Basic open-hearth process.
Chemical composition, in per cent.—P below .04; S below .06; Si below .04; Mn below .50.
Physical requirements as follows:

Shape.	Diameter in inches.	Ultimate strength; pounds per square inch.		Elastic ratio.	Elongation in 8 inches; per cent.	Reduction of area; per cent.
		Minimum.	Maximum.			
Rivet rods,	5/8	46000	55000	64.0	28.0	52
"	3/4	46000	54000	63.0	29.0	58
"	7/8	45000	54000	61.5	29.25	56
"	1	45000	54000	60.0	29.50	54
"	1 1/8	44000	54000	58.5	29 75	52
"	1 1/4	44000	54000	57.0	30.00	50

* Private communication, February 1896.

A rolled round about three-quarters inch in diameter, after being nicked about one-quarter way through, shall bend completely double without fracture, with the nick on the outer curve of the bend.

Heats rolled into bars less than five-eighths inch in diameter may be tested in trial rods of three-quarters inch.

If any bar fails to pass the physical tests, four more pieces shall be taken from the same heat, and the average of all five bars shall be considered the true record.

Rivets, when cut out of the work into which they have been put, shall show a tough silky structure, with no crystalline appearance.

See also general provisions in Section 171.

CLASS II.

Bridge Rivets; for Rivets in Railroad Bridges.

Method of manufacture.—Acid or basic open-hearth process.
Chemical composition, in per cent.—P below .04 in acid steel, below .03 in basic; S below .05; Si below .04; Mn below .50.
Physical requirements as follows:

Shape.	Diameter in inches.	Ultimate strength; pounds per square inch.		Elastic ratio.	Elongation in 8 inches; per cent.		Average reduction of area; per cent.
		Minimum.	Maximum.		Average.	Minimum.	
Rivet rods,	$\frac{5}{8}$	48000	57000	66.0	29.0	27.0	60
"	$\frac{3}{4}$	48000	56000	65.0	30.0	28.0	60
"	$\frac{7}{8}$	47000	56000	63.5	30.5	28.5	58
"	1	47000	56000	62.0	31.0	29.0	56
"	$1\frac{1}{8}$	46000	56000	60.5	31.0	29.0	54
"	$1\frac{1}{4}$	46000	56000	59.0	31.0	29.0	52

Two tons of bars from the same heat shall constitute a lot, and two specimens, each from a different bar, shall be tested from each lot. The above table gives the average required of these two bars, and the minimum below which no bar shall fall. If the average elongation or reduction of area on any one lot shall fall below the requirement, two additional bars shall be cut from the same lot, and the average of the four pieces shall be considered the average of the lot, provided that no concession be made in the minimum. Heats rolled into sizes less than five-eighths inch may be tested in trial rods of three-quarters inch.

A rolled round about three-quarters inch in diameter, after

being nicked one-quarter way through, shall bend completely double without fracture, with the nick on the outer curve of the bend. A piece of three-quarter-inch rod cut one-half inch long shall be upset while cold into a disc one-eighth inch thick, without developing extensive flaws or showing signs of cold shortness.

Rivets, when cut out of the work into which they have been put, shall show a tough silky structure, with no crystalline appearance.

See also general provisions in Section 171.

Class III.

Hard Bridge Rivets; a Substitute for Class II, Giving Greater Strength with Less Toughness.

Method of manufacture.—Acid or basic open-hearth process.
Chemical composition, in per cent.—P below .04 in acid steel, below .03 in basic; S below .05; Si below .04; Mn below .60.
Physical requirements as follows:

Shape.	Diameter in inches.	Ultimate strength; pounds per square inch.		Elastic ratio.	Elongation in 8 inches; per cent.		Average reduction of area; per cent.
		Minimum.	Maximum.		Average.	Minimum.	
Rivet rods.	5/8	54000	63000	61.0	28.0	26.0	55
"	3/4	54000	62000	60.0	29.0	27.5	55
"	7/8	53000	62000	58.5	29.5	27.5	53
"	1	53000	62000	57.0	30.0	28.0	51
"	1 1/8	52000	62000	55.5	30.0	28.0	49
"	1 1/4	52000	62000	54.0	30.0	28.0	47

Two tons of bars from the same heat shall constitute a lot, and two specimens, each from a different bar, shall be tested from each lot. The above table gives the average required of these two bars, and the minimum below which no bar shall fall. If the average elongation or reduction of area on any one lot shall fall below the requirement, two additional bars shall be cut from the same lot, and the average of the four pieces shall be considered the average of the lot, provided that no concession be made in the minimum. Heats rolled into sizes less than five-eighths inch may be tested in trial rods of three-quarters inch.

Rivets, when cut out of the work into which they have been put, shall show a tough silky structure, with no crytalline appearance.

See also general provisions in Section 171.

Class IV.

Common Hard Rivets; for Roof Trusses and other Structures not Exposed to Shock.

Method of manufacture.—Acid or basic open-hearth process.
Chemical composition, in per cent.—P below .06 in acid steel, below .04 in basic; S below .05; Si below .04; Mn below .60.
Physical requirements as follows:

Shape.	Diameter in inches.	Ultimate strength; pounds per square inch.		Elastic ratio.	Elongation in 8 inches; per cent.	Reduction of area; per cent.
		Minimum.	Maximum.			
Rivet rods,	5/8	54000	63000	61.0	27.0	55
"	3/4	54000	62000	60.0	28.0	55
"	7/8	53000	62000	58.5	28.5	53
"	1	53000	62000	57.0	29.0	51
"	1 1/8	52000	62000	55.5	29.0	49
"	1 1/4	52000	62000	54.0	29.0	47

Four tests shall be taken from each heat, and the average of these four shall conform to the above table. If the average elongation or reduction of area of any heat shall fall below the requirement, four additional bars may be cut from the same heat, and the average of the eight pieces shall be considered the average of the heat. Heats rolled into sizes less than five-eighths inch may be tested in trial rods of three-quarters inch.

Rivets, when cut out of the work into which they have been put, shall show a tough silky structure, with no crytalline appearance.

See also general provisions in Section 171.

Class V.

Soft Bridge Steel; for Angles, Plates, Bars, etc., for Bridges, Cranes, and Similar Structures Exposed to Shock.

Method of manufacture.—Acid or basic open-hearth process.
Chemical composition, in per cent.—P below .06 in acid steel, below .04 in basic; S below .07 in plates and angles, below .06 in eye-bars; Si below .04; Mn below .50.
Physical requirements as follows:

Shape.	Thickness in inches.	Ult. str.; lbs. per sq. inch. Minimum.	Ult. str.; lbs. per sq. inch. Maximum.	Elastic ratio.	Elongation in 8 inches; per cent.	Reduction of area; per cent.	Remarks.
Angles.	3/8	50000	58000	63.0	29.0	55	One piece of 3/4-inch angle must open out flat and another close shut without sign of fracture.
	1/2	50000	58000	61.5	29.0	53	
	5/8	49000	58000	60.0	29 0	51	
	3/4	49000	58000	58.5	29.0	49	
	7/8	48000	58000	57.0	29.0	47	
Plates.	5/16	53000	63000	65.0	23.0	44	On plates under 42 inches wide the required elongation shall be raised 1.5 per cent. and the reduction of area 2.0 per cent. On plates over 70 inches wide the elongation shall be lowered 1.5 per cent. and the reduction of area 2.0 per cent. On tests cut crosswise from the sheet, the minimum tensile strength shall be lowered 3000 pounds, the elongation 3 per cent., and the reduction of area 10 per cent. On universal-mill plates the allowance for transverse tests shall be 5000 pounds, 5 per cent. and 15 per cent. Both longitudinal and transverse strips cut from plates shall bend double flat. When every plate in the heat is tested, the minimum elongation and reduction shall be lowered 5 per cent.
	3/8	51000	61000	63.0	26.0	50	
	1/2	50000	60000	62.0	26.0	50	
	3/4	49000	59000	60.0	25.0	48	
	1	48000	58000	58.0	24.0	46	
	1 1/4	47000	58000	56.0	23.0	44	
Eye-bars, annealed.	3/4	50000	58000	57.0	. . . .	. .	The elongation in full length shall be 15 per cent. in bars from 10 to 20 feet long, 14 per cent. in 21 to 25 feet, 13.5 per cent. in 26 to 30 feet, and 13 per cent. in 31 to 35 feet.
	1	50000	58000	56.0	. . . .	. .	
	1 1/2	49000	58000	54.0	. . . .	. .	
	2	49000	58000	53.0	. . . .	. .	
	2 1/2	48000	58000	52.0	. . . .	. .	

Shapes.—In channels, beams, etc., the requirements on tests cut from the web shall be the same as for plates between 42 and 70 inches wide, with the same allowance for difference in thickness. In tests cut from the flange the minimum tensile strength shall be lowered 3000 pounds, the elongation 3 per cent., and the reduction of area 10 per cent..

See also general provisions in Section 171.

Class VI.

Medium Bridge Steel; a Substitute for Class V when Greater Strength and Less Toughness are Required.

Method of manufacture.—Acid or basic open-hearth process.
Chemical composition, in per cent.—P below .06 in acid steel, below .04 in basic; S below .07 in plates and angles, below .06 in eye-bars; Si below .04; Mn below .60.
Physical requirements as follows:

Shape.	Thickness in inches.	Ultimate strength; lbs. per sq. inch. Minimum.	Ultimate strength; lbs. per sq. inch. Maximum.	Elastic ratio.	Elongation in 8 inches; per cent.	Reduction of area; per cent.	Remarks.
Angles.	3/8	56000	64000	63.0	27.0	50	One piece of angle, not over ½ inch thick, shall open out flat, and another close shut without sign of fracture.
	1/2	56000	64000	61.5	27.0	48	
	5/8	55000	64000	60.0	27.0	46	
	3/4	55000	64000	58.5	27.0	44	
	7/8	54000	64000	57.0	27.0	42	
Plates.	5/16	59000	69000	62.0	22.0	39	On plates under 42 inches wide the required elongation shall be raised 1.5 per cent., and the reduction of area 2.0 per cent. On plates over 70 inches wide, the elongation shall be lowered 1.5 per cent., and the reduction of area 2.0 per cent. On tests cut crosswise from the sheet, the minimum tensile strength shall be lowered 3000 pounds, the elongation 3 per cent., and the reduction of area 10 per cent. On universal-mill plates the allowance for transverse tests shall be 5000 pounds, 5 per cent. and 15 per cent. Longitudinal strips shall bend double flat; transverse strips shall bend through 180 degrees around a pin 1 inch in diameter. When every plate in the heat is tested, the minimum elongation and reduction of area shall be lowered 5 per cent.
	3/8	57000	67000	60.0	25.0	45	
	1/2	56000	66000	59.0	25.0	45	
	3/4	55000	65000	57.0	24.0	43	
	1	54000	64000	55.0	23.0	41	
	1¼	53000	64000	53.0	22.0	39	
Eye-bars, annealed.	3/4	56000	64000	56.0	. . .	. .	The elongation in full length shall be 14 per cent. in bars from 10 to 20 feet long, 13 per cent. in 21 to 25 feet, 12.5 per cent. in 26 to 30 feet, and 12 per cent. in 31 to 35 feet.
	1	56000	64000	55.0	. . .	. .	
	1½	55000	64000	53.0	. . .	. .	
	2	55000	64000	52.0	. . .	. .	
	2½	54000	64000	51.0	. . .	. .	

SHAPES.—In channels, beams, etc., the requirements on tests cut from the web shall be the same as for plates between 42 and 70 inches wide, with the same allowance in thickness. In tests cut from the flange, the minimum tensile strength shall be lowered 3000 pounds, the elongation 3 per cent., and the reduction of area 10 per cent.

NOTE.—The allowable content of phosphorus may be raised to .08 per cent. for acid, and .05 per cent. for basic steel, if the best quality is not required, but other specifications must remain the same.

See also general provisions in Section 171.

Class VII.

Hard Bridge Steel.

Method of manufacture.—Acid or basic open-hearth process.
Chemical composition, in per cent.—P below .06 in acid steel, below .04 in basic; S below .07 in plates and angles, below .06 in eye-bars; Si below .05; Mn below .80
Physical requirements as follows:

Shape.	Thickness in inches.	Ultimate strength; lbs. per sq. inch. Minimum.	Ultimate strength; lbs. per sq. inch. Maximum.	Elastic ratio.	Elongation in 8 inches; per cent.	Reduction of area; per cent.	Remarks.
Angles.	3/8	60000	68000	62.0	26.0	48	One piece of angle, less than ½ inch thick, shall open out flat, and another piece close shut without sign of fracture.
	1/2	60000	68000	60.5	26.0	46	
	5/8	59000	68000	59.0	26.0	44	
	3/4	58000	68000	57.5	26.0	42	
	7/8	57000	68000	56.0	26.0	40	
Plates.	5/16	63000	73000	60.0	20.0	34	On plates under 42 inches wide the required elongation shall be raised 1.5 per cent., and the reduction of area 2.0 per cent. On plates over 70 inches wide, the elongation shall be lowered 1.5 per cent., and the reduction of area 2.0 per cent. On tests cut crosswise from the sheet, the minimum tensile strength shall be lowered 3000 pounds, the elongation 3 per cent., and the reduction of area 10 per cent. On universal-mill plates the allowance for transverse tests shall be 5000 pounds, 5 per cent. and 15 per cent. Longitudinal strips shall bend double flat. Transverse strips shall bend through 180 degrees around a pin 1 inch in diameter. When every plate in the heat is to be tested, the minimum elongation and reduction of area shall be lowered 5 per cent.
	3/8	61000	71000	58.0	23.0	40	
	1/2	60000	70000	57.0	23.0	40	
	3/4	59000	69000	55.0	22.0	38	
	1	58000	68000	53.0	21.0	36	
	1¼	57000	68000	51.0	20.0	34	
Eye-bars, annealed.	3/4	60000	68000	55.0	. . .	. .	The elongation in full length shall be 13 per cent. in bars from 10 to 20 feet long, 12.5 per cent. in 21 to 25 feet, 12 per cent. in 26 to 30 feet, and 11.5 per cent. in 31 to 35 feet.
	1	60000	68000	54.0	. . .	. .	
	1½	59000	68000	52.0	. . .	. .	
	2	59000	68000	51.0	. . .	. .	
	2½	58000	68000	50.0	. . .	. .	

Shapes.—In channels, beams, etc., the requirements on tests cut from the web shall be the same as for plates between 42 and 70 inches wide, with the same allowance for difference in thickness. In tests cut from the flange, the minimum tensile strength shall be lowered 3000 pounds, the elongation 3 per cent., and the reduction of area 10 per cent.

Note.—The allowable content of phosphorus may be raised to .08 per cent. in acid, and .05 per cent. in basic steel, if the best quality is not required, but other specifications must remain the same.

See also general provisions in Section 171.

Class VIII.

Extra Hard Bridge Steel; for Special Structures where Great Stiffness is Essential.

Method of manufacture.—Acid or basic open-hearth process.
Chemical composition, in per cent.—P below .06 in acid steel, below .04 in basic; S below .07 in plates and angles, below .06 in eye-bars; Si below .10; Mn below .80.
Physical requirements as follows:

Shape.	Thickness in inches.	Ultimate strength; lbs. per sq. inch. Minimum.	Ultimate strength; lbs. per sq. inch. Maximum.	Elastic ratio.	Elongation in 8 inches; per cent.	Reduction of area; per cent.	Remarks.
Angles.	3/8	64000	72000	61.0	25.0	45	One piece of angle, about 3/8 inch thick, shall open out flat, and another piece close shut without sign of fracture.
	1/2	64000	72000	59.5	25.0	43	
	5/8	63000	72000	58.0	25.0	41	
	3/4	62000	72000	56.5	25.0	39	
	7/8	61000	72000	55.0	25.0	37	
Plates.	5/16	67000	77000	59.0	18.0	32	On plates under 42 inches wide, the required elongation shall be raised 1.5 per cent., and the reduction of area 2.0 per cent. On plates over 70 inches wide, the elongation shall be lowered 1.5 per cent., and the reduction of area 2.0 per cent. On tests cut crosswise from the sheet, the minimum tensile strength shall be lowered 3000 pounds, the elongation 3 per cent., and the reduction of area 10 per cent. On universal-mill plates the allowance for transverse tests shall be 5000 pounds, 5 per cent. and 15 per cent. Longitudinal strips shall bend double flat. When every plate in the heat is to be tested, the minimum elongation and reduction of area shall be lowered 5 per cent.
	3/8	65000	75000	57.0	21.0	38	
	1/2	64000	74000	56.0	21.0	38	
	3/4	63000	73000	54.0	20.0	36	
	1	62000	72000	52.0	19.0	34	
	1 1/4	61000	72000	50.0	18.0	32	
Eye-bars, annealed.	3/4	64000	72000	54.0	. . .	. .	The elongation in full length shall be 12.5 per cent. in bars from 10 to 20 feet long, 12.0 per cent. in 21 to 25 feet, 11.5 per cent. in 26 to 30 feet, and 11.0 per cent. in 31 to 35 feet.
	1	64000	72000	53.0	. . .	. .	
	1 1/2	63000	72000	51.0	. . .	. .	
	2	63000	72000	50.0	. . .	. .	
	2 1/2	62000	72000	49.0	. . .	. .	

SHAPES.—In channels, beams, etc., the requirements on tests cut from the web shall be the same as for plates between 42 and 70 inches wide, with the same allowances for difference in thickness. In tests cut from the flange, the minimum tensile strength shall be lowered 3000 pounds, the elongation 3 per cent., and the reduction of area 10 per cent.

NOTE.—The allowable content of phosphorus may be raised to .08 per cent. for acid steel, and .05 per cent. for basic, if the best quality is not required, but other specifications must remain the same.

See also general provisions in Section 171.

Class IX.

Forging Steel; for Pins and Miscellaneous Forgings and for Special Plates and Angles.

Method of manufacture.—Acid or basic open-hearth process.
Chemical composition, in per cent.—P below .06 in acid steel, below .04 in basic; S below .07 in plates and angles, below .06 in eye-bars; Si below .10; Mn below .90.
Physical requirements as follows:

Shape.	Thickness in inches.	Ultimate strength; lbs. per sq. inch. Minimum.	Ultimate strength; lbs. per sq. inch. Maximum.	Elastic ratio.	Elongation in 8 inches; per cent.	Reduction of area; per cent.	Remarks.
Angles.	3/8	70000	80000	58.0	22.0	42	One piece of angle 3/8 inch thick shall open out flat, and another piece close shut without sign of fracture.
	1/2	70000	80000	56.5	22.0	40	
	5/8	69000	80000	55.0	22.0	38	
	3/4	68000	80000	53.5	22.0	36	
	7/8	67000	80000	52.0	22.0	34	
Plates.	5/16	73000	83000	56.0	16.0	30	On plates under 42 inches wide the required elongation shall be raised 1.5 per cent., and the reduction of area 2.0 per cent. On plates over 70 inches wide, the elongation shall be lowered 1.5 per cent., and the reduction of area 2.0 per cent. Longitudinal strips under 1/2 inch thick shall bend double flat. When every plate in the heat is to be tested, the minimum elongation and reduction of area shall be lowered 5 per cent.
	3/8	71000	81000	54.0	19.0	36	
	1/2	70000	80000	53.0	19.0	36	
	3/4	69000	79000	51.0	18.0	34	
	1	68000	78000	49.0	17.0	32	
	1 1/4	67000	78000	47.0	16.0	30	

When this steel is used for pins or forgings, a charge may be tested by rolling a small test ingot or piece of bloom into a bar with a cross-section of about 0.5 or 1.0 square inch. This bar should have an ultimate strength of between 70,000 and 80,000 pounds per square inch, an elastic ratio of 58 per cent., and an elongation of 15 per cent. in eight inches. This method will usually suffice to show the quality of the steel. If it is desirable to test the forged work, a bar should be cut from a rolled or hammered piece about six inches in smallest dimension, and turned to a three-quarter-inch round, two inches between shoulders. This should have an ultimate strength of between 67,000 and 80,000 pounds per square inch, an elastic ratio of 50 per cent., and an elongation of 20 per cent. in two inches. The test-piece should be cut at a depth of about two inches from the outside.

See also general provisions in Section 171.

CLASS X.

Hard Forging Steel; for Miscellaneous Forgings.

Method of manufacture.—Acid or basic open-hearth process.
Chemical composition, in per cent.—P below .05 in acid steel, below .03 in basic; S below .07; Si below .10; Mn below .90.
Physical requirements as follows:

Shape and origin of test-piece.	Ultimate strength; pounds per square inch. Minimum.	Ultimate strength; pounds per square inch. Maximum.	Elastic ratio.	Elongation; per cent.
A rolled bar with a cross-section of about 0.5 to 1.0 square inch, made from a bloom or test ingot. Elongation measured in 8 inches	75000	100000	55	12
A ¾-inch round, 2 inches long between shoulders, cut from a rolled or forged piece about 6 inches in smallest dimension. Elongation measured in 2 inches	75000	100000	45	15

The first method will suffice for ordinary work to show the quality of the material. The second involves considerable expense and delay in cutting and finishing the piece, and there is necessarily much variation caused by the different sizes and shapes of forgings. The test-piece should be cut at a depth of about two inches from the outside.

See also general provisions in Section 171.

CLASSES XI, XII, AND XIII.—For buildings, highway bridges, and other structures not exposed to shock.

The requirements on material for ordinary structures need not be so carefully drawn as in the case of railroad bridges. Hence it will suffice to accept the standard specifications of the Association of American Steel Manufacturers, as adopted at its meeting of August 9, 1895. They are here given in full, since the clauses relating to the inspection of material, and the allowance for overweights, apply equally to all classes of material. The Association did not limit the use of this metal to buildings not exposed to shock, for the matter of chemical composition was left open to the engineer, but in common with almost all manufacturers, I must unqualifiedly condemn the use of metal for a railway bridge that contains over .08 per cent. of phosphorus, while I believe that .06 per cent. should be the upper limit.

STANDARD SPECIFICATIONS GOVERNING THE PHYSICAL PROPERTIES OF STRUCTURAL STEEL AS ADOPTED BY THE ASSOCIATION OF AMERICAN STEEL MANUFACTURERS.

Process of manufacture.—Steel may be made by either the open-hearth or Bessemer process.

Test-pieces.—All tests and inspection shall be made at place of manufacture prior to shipment.

The tensile strength, limit of elasticity, and ductility, shall be determined from a standard test-piece cut from the finished material and planed, milled, or turned parallel. The elongation shall be measured on an original length of eight inches, except when the thickness of the finished material is five-sixteenths inch or less, in which case the elongation shall be measured in a length equal to 16 times the thickness; and except in rounds of five-eighths inch or less in diameter, in which case the elongation shall be measured in a length equal to eight times the diameter of section tested. Two test-pieces shall be taken from each melt or blow of finished material, one for tension, and one for bending.

Material which is to be used without annealing or further treatment is to be tested in the condition in which it comes from the rolls. When material is to be annealed or otherwise treated before use, the specimen representing such material is to be similarly treated before testing.

Every finished piece of steel shall be stamped with the blow or melt number, and steel for pins shall have the blow or melt number stamped on the ends. Rivet and lacing steel, and small pieces for pin plates and stiffeners, may be shipped in bundles securely wired together, with the blow or melt number on a metal tag attached.

Finish.—Finished bars must be free from injurious seams, flaws, or cracks, and have a workman-like finish.

Grades of steel.—Steel shall be of three grades, rivet, soft, and medium.

Rivet steel.—Ultimate strength, 48000 to 58000 pounds per square inch.

Elastic limit, not less than one-half the ultimate strength.

Elongation, 26 per cent.

Bending test, 180 degrees, flat on itself, without fracture on outside of bent portion.

Soft steel.—Ultimate strength, 52000 to 62000 pounds per square inch.

Elastic limit, not less than one-half the ultimate strength.

Elongation, 25 per cent.

Bending test, 180 degrees, flat on itself, without fracture on outside of bent portion.

Medium steel.—Ultimate strength, 60000 to 70000 pounds per square inch.

Elastic limit, not less than one-half the ultimate strength.

Elongation, 22 per cent.

Bending test, 180 degrees, to a diameter equal to thickness of piece tested, without fracture on outside of bent portion.

Pin steel.—Pins, made from either of the above-mentioned grades of steel, shall, on specimen test-pieces cut at a depth of one inch from surface of finished material, fill the physical requirements of the grade of steel of which they are made, for ultimate strength, elastic limit, and bending, but the required elongation shall be decreased five per cent.

Eye-bar steel.—Eye-bar material, 1½ inches and less in thickness, made of either of the above-mentioned grades of steel, shall, on test-pieces cut from finished material, fill the requirements of the grade of steel from which it is rolled. For thicknesses greater than 1½ inches there will be allowed a reduction in the percentage of elongation of one per cent. for each one-eighth of an inch increase in thickness, to a minimum of 20 per cent. for medium steel, and 22 per cent. for soft steel.

Full-size tests of steel eye-bars.—Full-size tests of steel eye-bars shall be required to show not less than 10 per cent. elongation in the body of the bar, and a tensile strength not more than 5000 pounds below the minimum tensile strength required in specimen tests of the grade of steel from which they are rolled. The bars will be required to break in the body, but should a bar break in the head, but develop 10 per cent. elongation and the ultimate strength specified, it shall not be cause for rejection, provided that not more than one-third of the total number of bars tested break in the head; otherwise the entire lot will be rejected.

Variation in weight.—The variation in cross-section or weight of more than 2½ per cent. from that specified will be sufficient cause for rejection,* except in the case of sheared plates ordered to gauge, when there will be permitted an excess of weight, over that corresponding to the dimensions on the order, equal in amount to that specified in the following table:

TABLE OF ALLOWANCE FOR OVERWEIGHT FOR RECTANGULAR PLATES.

Thickness of Plate.	Width of Plate. Up to 75 inches.	75 to 100 inches.
¼ inch.	10 per cent.	14 per cent.
5/16 "	8 "	12 "
⅜ "	7 "	10 "
7/16 "	6 "	8 "
½ "	5 "	7 "
9/16 "	4½ "	6½ "
⅝ "	4 "	6 "
over ⅝ "	3½ "	5 "

CLASS XIV.

Steel Castings.

Method of manufacture.—Acid open-hearth process.
Chemical composition, in per cent.—P below .04; S below .05; Mn below .80.
Physical requirements as follows:

Grade.	Shape and origin of test-piece.	Condition of test-piece.	Ultimate strength; lbs. per sq. inch. Minimum.	Maximum.	Elastic ratio.	Elongation; per cent.
Soft.	¾-inch round, 2 inches between shoulders, cut from a coupon or casting.	Annealed Natural	54000 57000	64000 67000	50 50	20 15
	A round or flat test-piece, rolled from a small test ingot of the heat from which castings are made. Tested in 8-inch length.	Natural	58000	68000	55	20
Hard.	¾-inch round, 2 inches between shoulders, cut from a coupon or casting.	Annealed Natural	60000 63000	70000 73000	50 50	15 15
	A round or flat test-piece, rolled from a small test ingot of the heat from which castings are made. Tested in 8-inch length.	Natural	64000	47000	55	15

NOTE.—No record shall be kept of test-bars exhibiting imperfections.

Recommendations.—It is recommended that the rolled test bar ("preliminary test") be used as a rule, and that the expense of cutting a piece from a casting be resorted to only occasionally as a check. Also, that castings of simple form be

* This clause will soon be changed by the association. A committee was appointed in April, 1896, to draft a sliding scale, so that the allowances on plates ordered to weight should be as reasonable as on those ordered to gauge.

used without annealing. Also, when a large number of similar pieces are to be made, that special bending or drop tests be devised, such tests, together with the chemical analysis, to be the sole requirements.

See also general provisions in Section 171.

SEC. 173.—*The quench-test.*—In these specifications there is nothing said about a quench-test, for I am of the opinion that it is an absurdity when applied to ordinary structural material. It was defended by Mr. Hunt* on the ground that it would guard against material that would be injured by careless heating and cooling in the mill or shops, but this suggests the query why such carelessness should be tolerated. It is assumed that the work is done by mills and shops that understand their business, and the steel should be made to fit the work in hand and not the ignorance of middlemen.

It is right to make the most severe tests on the cold properties, for the derailment of a train will subject certain members to great deformation; such an accident is always a possibility which human foresight seems powerless to avoid, but the carelessness in the shop stands on a different footing, for it is caused by positive and unnecessary acts in error.

Moreover, the quench-test depends very much upon slight differences in the methods of heating and cooling, differences which are almost imperceptible and unexplainable, and the same steel may be made to pass or fail under modes of treatment which seem to be inherently identical. It would appear, therefore, that no warrant exists for the imposition of this test upon the material for a railroad bridge, which is not calculated to withstand a conflagration followed by a flood. This position is being taken by a very large number of engineers, and a quench-test is rapidly becoming a thing of the past.

In concluding this chapter it may be well to quote the words of the chief of one of the most widely and favorably known plate mills of our country. The opinions are taken from a private letter, and, being never intended for publication, are free from all taint of business interest.

"I am honestly of the opinion that the complicated specifications that have been written in late years have really

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* *The Inspection of Materials of Construction in the United States. Journal I. and S. I.*, Vol. II, 1890, p. 312.

resulted in very little practical benefit to the consumer. Personally I should be willing to buy of the most reputable makers, trusting to them to use the proper care in manufacture, and relying rather on properly conducted bending tests and chemical analysis than on tensile tests; but as we probably cannot bring the engineer to this mind, I shall be very glad if anything can be done to moderate his misdirected zeal."

CHAPTER XIX.

WELDING.

SECTION 174.—*Influence of structure on the welding properties.*—Wrought-iron may be welded so that the point of union is as strong as the rest of the bar, for by upsetting the piece there can be an extra amount of work put upon the metal, and since the strength of the original bar was dependent upon the perfection of a great number of welds, it follows that the additional local heating and hammering may give a superior strength. Unfortunately, this is rarely the case, and it is seldom that failure does not take place in the neighborhood of the weld under destructive tests. It often does happen that a rod will break a short distance away from the actual point of union, but in spite of current supposition this by no means shows perfect workmanship, for it usually arises from the overheating of the iron at the point of fracture, without sufficient subsequent work to develop a proper structure.

In working steel the conditions are fundamentally different, for the bar is not a collection of fibres and welds but a thing complete in itself, so that it is impossible to make any improvement in a properly worked piece by cutting it in halves and putting it together again. It is quite conceivable that a bar may originally be underworked or overheated, and that additional local work can enhance the strength at the point of welding, but this assumption of a bad material to start with may be neglected. It is also possible to finish the hammering on a welded piece at a very low temperature and thereby exalt the ultimate strength beyond the true value, but inasmuch as this will give a less ductile and unreliable material, it will not be considered.

It is also possible, much more than with wrought-iron, to

have the weld stronger than a certain adjacent part of the bar, for the best of steel will be crystallized by high heat somewhat more readily than wrought-iron, and hence it can and often does happen that the metal in the neighborhood of a weld has a bad structure due to lack of hammering after high heating. The higher the critical temperature necessary to produce crystallization, the less is the danger from this source, so that, aside from the mere facility of welding at point of contact, the freedom from phosphorus and sulphur is a matter of prime importance, since both of these elements render the metal less able to withstand high temperatures.

The fundamental difference in crystallizing power between wrought-iron and steel makes a close comparison of the two impossible, but nevertheless it may be profitable to quote from Holley the following conclusions concerning iron.*

"(1) None of the ingredients except carbon in the proportions present seems to very notably affect the welding by ordinary methods. [The maximum percentages were P, .317; Si, .321; Mn, .097; S, .015; Cu, .43; Ni, .34; Co, .11; Slag, 2.262.]

"(2) The welding power by ordinary methods is varied as much by the amount of reduction in rolling as by the ordinary differences in composition.

"(3) The ordinary practice of welding is capable of radical improvement, the most promising field being in the direction of welding in a non-oxidizing atmosphere."

Sec. 175.—*Tensile tests on welded bars of steel and iron.*—A glance at the allowable contents of metalloids, as given in the foregoing synopsis, will show the wide gulf that separates iron from steel, and this will be still further indicated by Table 135, which gives the tensile tests on a series of welded steel bars of different compositions, the investigation having been conducted under my own direction. The total lack of certainty and regularity in the results is evident, and it should therefore be said that the smiths were men of long experience in handling steel, and they fully understood that the individual results were to be compared. The bars were of a size

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* *The Strength of Wrought-Iron as Affected by its Composition and by its Reduction in Rolling. Trans. A. I. M. E.*, Vol. VI, p. 101.

most easily heated and quickly handled, but notwithstanding these most favorable personal and physical conditions the record is extremely unsatisfactory.

In the case of the rounds, each workman has at least one bad weld against him, while there is only one heat which gave uniformly good results. Picking out the worst individual weld of each workman, blacksmith "*A*" obtained only 70 per cent. of the value of the original bar, "*B*," 54 per cent., "*C*,"

Table 135.

Tensile Tests on Welded Bars of Steel and Wrought-Iron.

Figures in parentheses indicate that the bar broke in the weld. N=natural bar; W=welded bar. * denotes that elongation is measured in 2 inches.

Kind of steel.	Conditions of test.	Composition; per cent.					N=natural. W=welded.	Elastic limit; pounds per square inch.	Ultimate strength; pounds per square inch.	Elongation in 8 inches; per cent.	Reduction of area; per cent.	Name of smith.
		C.	Mn.	P.	S.	Cu.						
Acid O. H. forging.	¾-inch round; lap weld.	.20	.89	.089	.03	.35	N	46670	70450	26.25	53.50	. . .
		. .	. . .	. . .	. . .	. . .	W	45890	(60940)	*10.00	19.73	A
		. .	. . .	. . .	. . .	. . .	W	45580	(55090)	*9.00	7.55	B
		. .	. . .	. . .	. . .	. . .	W	. . .	(40840)	*7.00	8.12	C
		. .	. . .	. . .	. . .	. . .	W	. . .	(42190)	*3.00	4.04	D
Acid Bess. forging.	¾-inch round; lap weld.	.25	1.36	.083	.05	.35	N	56140	86600	22.25	35.40	. . .
		. .	. . .	. . .	. . .	. . .	W	56750	(68810)	*4.00	29.29	A
		. .	. . .	. . .	. . .	. . .	W	. . .	(55020)	*6.00	0.78	B
		. .	. . .	. . .	. . .	. . .	W	. . .	(62060)	*5.00	6.50	C
		. .	. . .	. . .	. . .	. . .	W	. . .	(41930)	*3.00	2.10	D
Acid O. H. soft.	¾-inch round; lap weld.	.09	.46	.08	. . .	.35	N	40980	60680	30.00	53.20	. . .
		. .	. . .	. . .	. . .	. . .	W	38230	61060	*66.33	56.51	A
		. .	. . .	. . .	. . .	. . .	W	44660	60380	*36.00	58.50	B
		. .	. . .	. . .	. . .	. . .	W	45030	65610	. . . .	56.28	C
		. .	. . .	. . .	. . .	. . .	W	. . .	(26640)	*12.00	4.53	D
Acid O. H. soft.	¾-inch round; lap weld.	.09	.39	.076	. . .	.35	N	38940	56900	28.75	59.89	. . .
		. .	. . .	. . .	. . .	. . .	W	37550	57650	*39.00	62.18	A
		. .	. . .	. . .	. . .	. . .	W	37400	(42740)	*9.00	13.48	B
		. .	. . .	. . .	. . .	. . .	W	40910	(43910)	*10.50	14.55	C
		. .	. . .	. . .	. . .	. . .	W	39220	58790	*34.00	62.29	D
Acid O. H. soft.	¾-inch round; lap weld.	.09	.40	.08	. . .	.35	N	41670	56300	30.00	62.56	. . .
		. .	. . .	. . .	. . .	. . .	W	33740	(39490)	*6.00	8.63	A
		. .	. . .	. . .	. . .	. . .	W	. . .	(30550)	*7.00	10.79	B
		. .	. . .	. . .	. . .	. . .	W	38300	53880	*37.00	65.46	C
		. .	. . .	. . .	. . .	. . .	W	34460	50020	*16.00	23.22	D
Basic O. H. soft.	¾-inch round; lap weld.	.06	.55	.019	. . .	.35	N	33880	51760	32.75	65.35	. . .
		. .	. . .	. . .	. . .	. . .	W	37660	58650	*32.00	59.55	A
		. .	. . .	. . .	. . .	. . .	W	. . .	(30640)	*8.00	13.88	B
		. .	. . .	. . .	. . .	. . .	W	35370	(51850)	*27.00	46.77	C
		. .	. . .	. . .	. . .	. . .	W	31820	49690	*41.00	67.85	D
Basic O. H. soft.	¾-inch round; lap weld.	.06	.30	.014	. . .	.35	N	32580	48990	31.75	71.56	. . .
		. .	. . .	. . .	. . .	. . .	W	41930	54530	*36.00	66.68	A
		. .	. . .	. . .	. . .	. . .	W	35470	52100	*39.00	70.81	B
		. .	. . .	. . .	. . .	. . .	W	38280	54200	. . . .	72.81	C
		. .	. . .	. . .	. . .	. . .	W	39720	55110	*41.00	70.61	D

TABLE 135.—Continued.

Kind of steel.	Conditions of test.	Composition; per cent. C.	Mn.	P.	S.	Cu.	N=natural. W=welded.	Elastic limit; pounds per square inch.	Ultimate strength; pounds per square inch.	Elongation in 8 inches; per cent.	Reduction of area; per cent.	Name of smith.
Basic O. H. soft.	¾-inch round; lap weld.	.08	.50	.027	.	.35	N	39820	62000	30.00	55.96	...
		...	...	...	...	...	W	37330	(49210)	*9.00	8.22	A
		...	...	...	...	...	W	40880	69460	*30.00	48.15	B
		...	...	...	...	...	W	44510	68380	...	48.54	C
		...	...	...	...	...	W	...	(55560)	*17.00	...	D
Acid Bess. soft.	2x⅜-inch flats; lap weld.	.06	.36	.032	.054	.69	N	40780	59140	29.50	47.65	...
		...	...	...	...	...	W	42780	50560	7.50	21.00	...
		.06	.40	.032	.054	.69	N	42020	61370	25.00	46.89	...
		...	...	...	...	...	W	45150	55780	8.50	24.78	...
		.06	.45	.032	.054	.69	N	40740	60730	26.25	46.72	...
		...	...	...	...	...	W	46720	58540	5.00	19.48	...
		.06	.35	.032	.054	.69	N	42680	60780	28.75	47.23	...
		...	...	...	...	...	W	43350	48740	1.25	20.20	...
Basic O. H. soft.	2x⅜-inch flats; scarf weld.	.08	.17	.008	.016	.10	N	30300	45070	39.00	69.70	...
		...	...	...	...	...	W	31690	43290	11.25	42.16	...
		.11	.32	.011	.029	.08	N	33600	50190	33.75	58.48	...
		...	...	...	...	...	W	...	45900	8.50	34.11	...
		.11	.32	.006	.018	.11	N	35730	49580	33.00	56.92	...
		...	...	...	...	...	W	32120	45280	10.00	22.18	...
		.09	.29	.005	.021	.10	N	36390	50050	33.00	59.82	...
		...	...	...	...	...	W	37400	45280	7.50	41.08	...
Basic O. H. soft.	2x⅜-inch flats; lap weld.	.12	.36	.005	.022	.08	N	34580	51080	28.50	48.63	...
		...	...	...	...	...	W	30840	41600	7.50	26.34	...
		.13	.39	.005	.025	.10	N	35470	50770	33.75	51.50	...
		...	...	...	...	...	W	...	37000	7.50	29.88	...
		.12	.29	.005	.016	.10	N	36830	51300	31.25	52.62	...
		...	...	...	...	...	W	33300	43530	7.00	29.31	...
		.12	.51	.005	.021	.09	N	37650	54770	26.25	41.94	...
		...	...	...	...	...	W	35200	48280	7.00	21.74	...
Wrought-iron.	2x⅜-inch flats; lap weld.	...	...	...	...	...	N	33390	50080	23.50	27.26	...
		...	...	...	...	...	W	32050	39320	6.00	15.52	...
		...	...	...	...	...	W	34060	40620	6.25	22.26	...
		...	...	...	...	...	W	32700	45140	11.75	20.98	...
		...	...	...	...	...	W	32040	44730	11.00	19.25	...
		...	...	...	...	...	W	32760	38430	4.00	9.36	...

58 per cent., and "*D*" only 44 per cent. The forging steel showed one weld with only 48 per cent., the common soft steel 44 per cent., while even the pure basic steel gave one test as low as 59 per cent. In some cases where the break took place away from the weld, the elongation was nearly up to the standard, this being true of the four tests of the last heat on page 362, and it should be noted that this metal contained .35

per cent. of copper, but in the other pieces the stretch was low and the fracture so silvery that it was plain the structure of the bar had been ruined. In most cases where the test-bar broke in the weld, the pieces parted at the surfaces of contact, showing that no true union had taken place; one or two fractures were homogeneous, but they showed the coarse crystallization that follows overheating.

The lap welds represent the method ordinarily used in making pipe, and are really a better criterion of the welding quality of the steel than the round pieces, for in making the union the pieces were simply laid together with no upsetting, and hence there was less chance for the manipulations of the smith. All of this steel, both Bessemer and open-hearth, had been pronounced suitable for the making of pipe, although it will be a revelation to most metallurgists that such a high content of copper could possibly be allowed. In all cases the bars broke across the weld with a more or less crystalline fracture, there being no instance where the separation was at the plane of union, so that, while thorough welding was proven, it was also evident from the lessened ductility that the metal was overheated during the operation.

TABLE 136.

Welding Tests by the Royal Prussian Testing Institute.

Kind of metal.	Ult. strength; pounds per square inch.		Per cent. elongation in 200 m. m. =7.87 inches.		Per cent. reduction of area.	
	Av. 6 tests, natural.	Av. 9 tests, welded.	Av. 6 tests, natural.	Av. 9 tests, welded.	Av. 6 tests, natural.	Av. 9 tests, welded.
Medium O. H. steel	72110	41820	20.8	3.2	34.9	4.5
Soft O. H. steel	64570	45800	25.1	5.1	44.7	10.5
Puddled iron	57890	47080	22.2	7.7	39.5	14.0

The figures on the iron bars show that the situation is no better than with steel, for the welded bars are far inferior to the natural piece both in strength and ductility. The general truth of these experiments is corroborated by Table 136, which gives a condensation of the results on a series of tests made by the Royal Prussian Testing Institute, the data being translated into American form.*

* *Journal I. and S. I.*, Vol. I, 1883, p. 425, *et seq.*

The average tensile strength of the welded bars of medium steel was 58 per cent. of the natural, the poorest bar showing only 23 per cent. In the softer steel the average was 71 per cent. and the poorest 33 per cent., while in the puddled iron the average was 81 per cent. and the poorest 62 per cent. The complete destruction of ductility is conclusively shown in the case of all three metals, even the wrought-iron being hopelessly wrecked.

As above stated, the flat bars given in Table 135 were such as had been used successfully in making pipe which would stand all the ordinary tests of distortion, while the soft basic metal, made to fill the stringent requirements of the United States Government, would meet the most severe tests. Such metal is used regularly in certain branches of manufacture where the best welding qualities are required, and the users are firmly convinced that "the weld is perfect."

It may be possible to produce better results by special arrangements, but it must certainly be acknowledged that a weld as performed by ordinary blacksmiths and by the usual methods on the best metal, whether iron or steel, is not nearly as good as the rest of the bar; and it is still more certain that welds of large rods of common forging steel are entirely unreliable and should not be employed in any structural work. Electric methods do not offer a solution of the problem, for during the process the metal is heated far beyond the critical temperature of crystallization, and only by heavy reductions under the hammer or press can much be done toward restoring the ductility of the piece. In many cases this subsequent hammering is impracticable owing to the consequent deformation of the piece.

SEC. 176.—*Influence of the metalloids upon the welding properties.*—The way in which the impurities of the metal affect the welding power has been a matter of discussion, it having even been supposed that they act simply by interposition, and, again, that they increase the susceptibility of the iron to oxidation. I believe both of these theories are wrong. If the first were true, then one per cent. of carbon would have the same effect as one per cent. of sulphur, which is manifestly not the case. The second theory does not hold, since sulphur, which is notoriously one of the worst enemies

of welding, is not oxidized either in the acid Bessemer or open-hearth furnace, and there is no ground for assuming that it oxidizes in welding. It will also be seen that as phosphorus, carbon, and manganese protect iron from burning in the Bessemer and open-hearth, so they must also tend to be preferentially oxidized in a blacksmith's fire, and thus by preventing the formation of iron oxide, as well as by the formation of a liquid flux containing phosphoric acid and oxide of manganese, they should, as far as oxidation is concerned, assist rather than retard the welding.

A third theory is advanced that the impurities affect the mobility. When half of one per cent. of carbon is added to the metal, it produces a compactness or hardness, even when the steel is hot, that must prevent the easy flowing together that follows a pressure upon two pieces of white-hot wrought-iron or soft steel. A higher temperature can not be used because every increase in carbon reduces the safe working temperature at the same time that it increases the stiffness.

This decrease in mobility doubtless plays an important part in the explanation, but I believe that a greater influence is to be found in what may seem at first sight to be the same thing but which in reality is a different quality, *viz.:* The power, or property, of passing through a viscous state on the road to liquidity. There are other metals, lead and copper for instance, which are malleable and ductile, but which do not go through a history of slow softening under the application of heat, the change to a liquid state being sudden and without any marked intermediate stage. Pig-iron is of the same character, for no matter how low the other metalloids may be, the presence of three per cent. of carbon produces a metal which changes suddenly from a solid to a liquid state, and it is reasonable to suppose that each increment of carbon, phosphorus, and manganese tends in the same direction.

In addition to this effect, I believe that an equally important factor exists in the action of carbon, phosphorus, sulphur, and copper in destroying the quality of cohesion by increasing the tendency to crystallization, for it is well known that these metalloids lower the point at which the steel becomes what is incorrectly, but quite naturally, called "burned." When the steel is overheated it crumbles under the hammer, and it

is plain that it can not be easily united to another piece when it is incapable of remaining united to itself. This theory also explains what seems to be a fact, that a small proportion of manganese aids in welding, for although it does decrease the mobility at any particular temperature, it allows a higher heat to be put upon the metal without the creation of a destructive crystallization, and thus indirectly renders possible a greater mobility and maintains a more favorable internal molecular structure.

The following conclusions summarize what has just been given and seem to fit the theory and the facts:

(1) With the exception of manganese in small proportion, the usual impurities in steel reduce its welding power by lowering the critical temperature at which it becomes coarsely crystalline.

(2) A small content of manganese aids welding by preventing crystallization.

(3) Only the purest and softest steel can be welded with any reasonable assurance of success.

(4) The confidence of a smith in his own powers and his belief in the perfection of the weld, is no guarantee that the bar is fit to use.

CHAPTER XX

STEEL CASTINGS.

SECTION 177.—*Definition of a steel casting.*—Within the last few years steel castings have come into general use in the structural world, but there is still a lamentable ignorance concerning their nature. A steel casting by very definition must be made of steel which is cast in a fluid state into the desired shape. This leaves open to discussion the great question considered in Chapter IV as to what is included in the term "steel," but although the making of a general definition is complicated by the possibility of producing "puddled steel," there is no necessity of introducing this qualification into remarks on castings, since fluidity is an essential feature. As for the distinction between "steel" and the so-called "ingot iron", it is needless to say that endless confusion would be introduced in the trade if the soft products of the open-hearth were to be styled "iron castings."

Notwithstanding the plain limits which have been set by metallurgy and common sense, there is a cloud of error hanging around the term "steel castings," which is due partly to ignorance and partly to deliberate fraud. It has been the practice of some persons to make castings from a mixture of pig-iron and steel melted in a cupola, although every metallurgist and every foundryman of intelligence knows that the metal is altered very much by remelting, and that the changes in silicon, manganese, and carbon depend on all the varying and uncertain factors of temperature and exposure. In melting ordinary pig-iron, the carbon usually changes very little, for, by the nature of the case, the content of this metalloid was adjusted in the blast-furnace to about the absorptive capacity corresponding to the manganese and silicon, and as the conditions in the cupola are similar to

those in the blast-furnace, it follows that a metal which is the normal product of one will not be fundamentally altered by passing through the other.

But a mixture of steel and iron is not a normal product of any furnace, and in its treatment in the cupola there is a tendency to make radical changes in the composition by the absorption of carbon. Thus, by the unnatural union of pig and scrap, and by the uncertain changes in silicon, manganese, and carbon, there is produced a hybrid metal which is useful for special purposes, but which is fundamentally different from any kind of steel. It is true that scrap and iron are melted together to make open-hearth steel, but this is done under an oxidizing flame and, either during the melting or afterward, the metalloids are almost entirely eliminated, giving a definite starting point from which a known and regular metal can be made by the addition of proper recarburizers.

Sometimes castings of cupola metal, made either with or without scrap, are heated in contact with iron oxide in order to burn the contained metalloids. The product is a more or less tough metal, known as malleable iron, which is extensively employed in making small, thin, or complicated shapes that could scarcely be poured in steel, but which can be made of the more liquid iron. The attempt has been made to call these "steel," and the claim has been fortified by analyses showing that the composition resembles that of some steel. The argument is too shallow for consideration, since, on the same basis, the product of the puddle-furnace or the charcoal bloomary might be termed "mild steel." Malleable iron must always be inferior to steel, because any oxides of silicon, manganese, phosphorus, or iron which are formed remain diffused throughout the mass, thereby breaking to some extent the bond of continuity.

Such castings are useful in a certain field, for they are far tougher than cast-iron, and they may even enter into competition with steel castings, but they must always bear a different name, since steel castings must necessarily be made by pouring into finished shape the melted product of a crucible, a Bessemer converter, or an open-hearth furnace.

SEC. 178.—*Methods of manufacture.*—The crucible process is sometimes employed for small castings, since the condi-

tions of the "dead-melt" give a much more quiet metal, evolving less gas in contact with cold surfaces, and the casting is more apt to be free from blow-holes. In certain special cases, as in the manufacture of big guns at Krupp's, the crucible has been used in making large masses of metal, but its great cost must prohibit its adoption for general structural work.

The Bessemer has been used to some extent in the past for making steel castings, but it is utterly unfitted for the work on account of the great cost of the operation when only two or three heats are required during the day. One way of obviating this is by taking an occasional heat from a Bessemer plant which is running regularly on other products, but this supposes, what is seldom the case, that the mixture is low in phosphorus. The day has passed away when a casting could be made of ordinary steel, and as it is now necessary to make a careful selection of the stock so that the content of phosphorus shall not exceed .04 per cent., the melting furnace is the cheapest as well as the most efficient instrument of production.

Within the last few years there has been a revival of Bessemer castings due to special developments along certain lines of procedure which have been practiced in exceptional cases for many years. After the drop of the carbon flame, a certain amount of melted ferro-silicon is added to the bath and the blowing resumed. The silicon is oxidized and produces a very high temperature, so that the steel can be poured into very small castings without danger of scull.

This latter point is one of the most important advantages claimed for this method of manufacture. It may be well, therefore, to say that there is no difficulty at all in a good open-hearth furnace in making steel just as hot as can be wanted; in fact, considerable care must be exercised to keep the metal from being too hot. On some kinds of work an excess of temperature may not cause trouble, but in other cases the open-hearth furnace offers far better opportunities for that complete control of temperature and casting conditions which is so desirable and so essential.

The open-hearth furnace also allows more perfect control over the casting conditions. A basic hearth is sometimes

used and has a slight advantage in the ability to make low phosphorus without much extra cost, but basic metal seems to be more "lively" in casting, and hence there is greater danger of honeycombs. The expense account of molding, drying, and chipping is so great under any system of manufacture that it does not pay to save a dollar a ton on the raw material when four times as much is lost on the finished products, and it will be found that the true way to make good castings is to melt the best obtainable stock in an acid-lined open-hearth furnace.

SEC. 179.—*Blow-holes.*—The use of good stock determines to a great extent the nature of the product, but it does not in the least influence the solidity of the castings. This depends partly on the temperature and composition of slag and metal before tapping, and partly on the quantity and nature of the recarburizing additions. An increase in these latter agents covers up the errors in furnace manipulation, but shows itself in a higher content of metalloids. Honeycombed metal may arise from bad casting conditions or it may come from a laudable desire to reduce to the lowest possible point the proportions of silicon and manganese, for the manufacturer well knows that the blow-holes decrease only slightly the strength and toughness of a casting, while the complete removal of them by overdoses of metalloids gives a brittle metal.

It is the current impression that during the last few years all the difficulties in making sound castings have been completely overcome by the introduction of metallic aluminum and certain alloys of silicon. It is true that great progress has been made, but there is no magic wand for sale which can be waved over a ladleful of steel to "kill" it "dead." Hadfield,* in an able article on the use of aluminum, says: "There is no rapid or royal road to the production of sound steel castings; this is only attained by long experience combined with specialized knowledge."

Some engineers specify that the cavities shall not exceed a certain percentage of the total area, but the common-sense method is to clothe the inspector with discretionary power, for a flaw may be perfectly harmless on the under surface of a base-plate when it would be fatal in the rim of a wheel. In

* *Aluminum Steel. Journal I. and S. I.*, Vol. II. 1890, p. 174.

this connection it should be noted that there is a radical difference between a "blow-hole" and a "pipe." The cavities which may often be seen where the "sink-head" or "riser" is cut off, are not evidence of unsoundness but exactly the opposite, for they show that feeding has continued after the riser was exhausted, and that the hidden interior has been rendered solid at the expense of the visible surface.

SEC. 180.—*Phosphorus and sulphur in steel castings.*—In writing the specifications for steel castings, the most important point is to state that phosphorus shall not exceed .04 per cent. An excess of the other elements may be guarded against by requiring a proper ductility, but phosphorus, although influencing to some extent the ordinary testing history, is often masked by other factors, and manifests itself only at a later time in that brittleness under shock which is its inherent characteristic. This is an important matter in the case of rolled metal, but it is of much more vital moment in steel castings, for these will generally fail, not by being pulled and stretched to destruction, but by sudden strain and shock.

The content of sulphur is of little importance to the user, for it affects the cold properties very slightly, but it will do no harm to specify that it shall not be over .05 per cent., good castings generally containing less than this proportion. Copper need not be mentioned, for there is no evidence that it has any influence upon the finished casting.

SEC. 181.—*Effect of silicon, manganese, and aluminum.*—The elements used to procure solidity are silicon, manganese, and aluminum. Their value to the steelmaker is due in great measure to their power of uniting with oxygen, the action being as follows :

3.44 parts	manganese	unite with	1.00 part	of oxygen.
3.44 "	aluminum	" "	3.01 parts	"
3.44 "	silicon	" "	3.93 "	"

Hence the aluminum is three times, and the silicon four times, as efficient as manganese, weight for weight, while they have an additional value from their greater affinity for oxygen, since this enables them to seize the last traces from the iron and wash the bath so much the cleaner.

Another function which may play a part in the operation

is the increase in capacity to dissolve or occlude gases, and as far as the value of the casting is concerned this will be equivalent to destroying them. It is not known how far this determines the situation, but it is evident that it has no connection with the power to unite with oxygen. It was once thought that aluminum increased the fluidity of steel by lowering the point of fusion, but experiments with a Le Chatelier pyrometer* gave the same melting point of 1475° C. for ordinary soft steel as for an alloy with five per cent. of aluminum. The tendency of both aluminum and silicon is to make the steel creamy and sluggish; it is true that such metal will run through small passages without chilling better than ordinary steel, but this is because the latter foams and froths when in contact with cold surfaces, and the flow is thereby impeded and sufficient surface exposed to chill the advance guard of the stream.

The percentage of manganese should not exceed .70 in soft castings nor .80 in harder steels, since more than this may render the metal liable to crack under shock. Silicon can be present up to .10 per cent. in the mild steels and .35 per cent. in the hard without any appreciable diminution in toughness. Aluminum is seldom present except in traces, and should not be over .20 per cent., for it decreases the ductility. The carbon must vary according to the desired tensile strength and the use to which the casting is to be put. When it is over .70 per cent. the steel becomes so hard that machining is slow, and there is danger of lines of weakness from shrinkage in complicated shapes.

SEC. 182.—*Physical tests on soft steel castings.*—Since the failure of cast-work is almost always due to sudden strain, it is the safer plan to have the metal for common purposes between .30 and .50 per cent. in carbon, but when great toughness is required it should not be over .15 per cent. This latter specification also presupposes a low content of manganese, silicon, and, above all, of phosphorus; with this composition the casting displays all the characteristics usually associated with the toughest of rolled shapes. A test on an unannealed gear-wheel of such metal, manufactured by The

* See article on *Pyrometric Data*, by H. M. Howe, *Engineering and Mining Journal*, October 11, 1890, p. 426.

Pennsylvania Steel Company, was made by cutting the rim between the spokes and then bending one arm to a right angle, twisting another through more than 180° without sign of fracture, while a third was hot-forged from a star-shaped section of about 2 inches by 1½ inches into a bar 1¼ inches by three-eighths inch, and after being cooled was twisted into a closed corkscrew. Similar pieces were exhibited by Krupp in his magnificent exhibit at Chicago, but we stand ready in America to duplicate any such metal on regular contracts.

Such trials, made on castings taken at random, are far preferable to tensile tests from sample bars, since the small pieces will not be in exactly the same physical condition as the larger castings. Such bars have a certain value, however, and avoid the necessity of spoiling good finished work. It is well to keep in mind that a flaw or blow-hole in the small test does not necessarily imply that the casting contains similar imperfections, and also that while an open cavity, however small, which is visible on the surface of a machined test will have a disastrous effect upon the strength and ductility, it might be of slight importance if buried in the interior. This necessity of having a perfect surface makes it difficult to conduct a long series of tests with exactly the same dimension of test-piece, for if five-eighths inch in diameter is the desired size, it may be necessary to turn some of the pieces to one-half inch, while the length must sometimes be reduced to 6 or to 4 inches.

This test-piece should not be annealed unless the castings themselves are to be treated in the same manner, and although it is customary to anneal most structural work, the trouble is not necessary in a great many cases if the very best of stock is used. This statement will be called heretical by many engineers, but the tests that have just been recorded upon an unannealed gear-wheel will show that the metal can be exceptionally tough in its original state.

The Pennsylvania Steel Company has made hundreds of very thin gear-wheels of considerable size for use in agricultural machinery, where everything is sacrificed to lightness, and although none of these have been annealed we have yet to hear of complaints of breakage. We have also made many rolls and pinions for rolling mills, and these are exposed to

the most arduous service of stress and shock, but they almost always wear out rather than break.

It is undeniable that proper annealing gives a finer grain to a casting of good composition, but, on the other hand, it does not affect the grain if the metal is high in phosphorus. It is also certain that reheating removes internal strains, so that it would be of advantage in very complicated castings, especially where the interior corners are very sharp, but such corners can almost always be avoided by a little care.

It will be granted that the agricultural gear-wheels just mentioned must, by virtue of their shape and thinness, be subject to severe internal strains, and if annealing can be dispensed with in their case, it is certainly unnecessary in many other cases when the very best stock is used. It is the general opinion that annealing is advisable and even necessary, but I repeat that The Pennsylvania Steel Company, while it does so treat its product when demanded by the specifications, does not apply this process to castings that are to be used in its own rolling mills, since the metal in its natural state seems to be able to withstand all that would be expected of an annealed piece.

Up to within a few years most steel castings were made of hard metal containing from .30 to .50 per cent. of carbon, and having a tensile strength of 80,000 to 100,000 pounds per square inch. But just as engineers have long since learned that the strongest and safest bridge is not built of rolled steel with .30 per cent. of carbon, so they must learn that in still greater measure it would be better to use a softer metal in castings.

Table 137 gives the results of tests made on sample bars of cast steel, showing the composition and physical qualities.

The silicon is not given, but it was below .05 per cent. in every case. The test-piece was not cut from the casting itself, but from a small coupon which is much more likely to contain blow-holes, and this will explain why it was often necessary to pull the piece in a 6-inch length. The test was round in every case, and therefore gave slightly worse results than a flat, but this is far from explaining the great inferiority of the casting when compared with the preliminary test, or the much more marked difference from what should be expected in properly rolled steel of similar tensile strength.

The results show what has so often been mentioned in these pages—that the ultimate strength and elastic limit are altered very little by the amount of work upon the piece as long as it is not finished at a low temperature. Thus, in the annealed casting the elastic limit is 56.62 per cent. of the ultimate strength, while in the annealed bars rolled from the ingot it is 57.39 per cent. This approximation is remarkable because the factors relating to ductility show that the physical state of the two metals must be radically different.

TABLE 137.

Comparative Physical Properties of Bars Cut from Annealed Soft Steel Castings and Unannealed Bars of the Same Heats Rolled from 6-inch Square Ingots, Together with Results of Similar Bars Made from Large Ingots.

Steel manufactured by The Pennsylvania Steel Company.

Heat number.	Composition; per cent.				Ultimate strength; pounds per square inch.	Elastic limit; pounds per square inch.	Elongation; per cent., part in 8 inches, part in 6 inches.	Reduction of area; per cent.
	C.	P.	Mn.	S.				
3552	.17	.027	.65	.034	58190	34290	24.00	32.1
3555	.17	.027	.66	.056	56030	32440	14.90	19.7
3557	.17	.032	.60	.029	55880	32750	27.13	42.3
3559	.17	.027	.65	.038	55350	30350	23.10	42.5
3563	.17	.024	.62	.024	59390	34790	20.10	34.5
3565	.23	.029	.65	.025	60060	33130	20.65	26.8
3568	.14	.029	.70	.032	58320	31750	17.25	20.8
3571	.18	.033	.58	.028	56700	30670	26.88	46.7
3573	.17	.028	.67	.027	57440	31430	21.66	36.7
3573	.17	.036	.70	.027	58860	34260	22.04	29.8
3577	.17	.037	.59	.029	57980	33220	23.00	39.3
3578	.17	.045	.67	.026	58810	33510	22.16	30.4
3579	.15	.037	.63	.028	54940	32190	22.75	47.0
3580	.18	.038	.71	.017	58970	34180	22.25	36.7
3582	.17	.036	.63	.024	56380	31520	13.00	25.5
3583	.18	.032	.61	.022	59400	35330	14.13	18.8
3584	.18	.027	.60	.027	55970	29690	22.38	32.1
3586	.17	.027	.60	.027	55630	30300	18.50	31.4
3588	.16	.043	.63	.031	56950	32530	26.50	42.7
3592	.18	.027	.69	.028	59050	32940	20.00	33.0
Average of annealed cast bars.	.17	.032	.64	.029	57515	32564	21.12	33.44
2x⅜-inch bars rolled from 6-inch square ingots cast from the same heats and tested in natural state.					63523	42700	24.74	43.80
Average of 2x⅜-inch bars rolled from 4-inch billets made from 16-inch ingots of 7 different heats of about the same tensile strength as the above castings.				Natural Annealed	62089 55021	42441 31576	30.14 30.36	60.86 60.00

SEC. 183.—*Physical tests on medium hard steel castings.*— It has just been shown that the average elastic ratio in annealed castings is about the same as in annealed rolled bars, but there will be much greater variations between individual tests in the case of the unworked metal owing to local imperfections, and there will also be greater variations with a stronger steel. This will be shown by Table 138, which gives the results on duplicate bars from four different heats of harder metal.

TABLE 138.

Physical Properties of Annealed Bars cut from Castings of Medium Hard Steel; all bars $\frac{3}{4}$ inch in Diameter.

Manufactured by The Pennsylvania Steel Company.

Heat number.	Composition; per cent.					Ultimate strength; pounds per square inch.	Elastic limit; pounds per square inch.	Elongation in 2 inches; per cent.	Reduction of area; per cent.	Elastic ratio; per cent.
	C.	Mn.	P.	S.	Si.					
921	.20	.54	.026	.022	.30	60580	33710	30.50	38.57	55.6
						60680	32380	36.50	51.90	53.4
						60830	32750	36.00	44.34	53.8
						61480	30740	32.00	39.80	50.0
						62420	32460	38.00	50.90	52.0
953	.22	.56	.035	.034	.30	63320	37400	36.00	46.33	59.1
						64880	34170	24.50	28.57	52.7
						65500	44850	29.00	39.40	68.5
						65845	33595	26.00	32.40	51.0
						65930	32290	30.00	33.37	49.0
						67010	48630	26.00	32.40	72.6
974	.38	.75	.029	.023	.35	72630	44940	16.00	20.70	61.9
						75240	45880	23.00	31.63	61.0
966	.35	.68	.038	.034	.34	73090	45390	17.50	21.25	62.1
						75160	45510	20.50	27.64	60.6

It will be seen that the ultimate strength is fairly regular, and this indicates that the metal itself is homogeneous but that minute imperfections give rise to the variations in the elongation, reduction of area, and elastic ratio. In the body of a casting these defects exert little influence, but they seriously affect the integrity of a small machined piece. This will emphasize the statement already made that the safest way, whenever practicable, would be to make a drop test on a sample casting rather than to cut a small bar from the piece or from a separate coupon.

CHAPTER XXI.

INSPECTION.

SECTION 184.—*Causes of friction between manufacturer and inspector.*—Nothing is easier than to write in one sentence the self-evident laws that should govern the inspection of steel, for the manufacturer should supply exactly what is required and the inspector should receive nothing else. If the steel does not fulfill the specifications, it is most certainly the fault of the maker, and all the chances and losses of error should have been taken into consideration in making the contract. Moreover, the inspector is only an agent, and he violates his trust in accepting anything that falls outside the limits which, either wisely or foolishly, have been set by his principal.

These facts are patent, and it may seem strange that any misunderstanding can possibly come in their practice; but such trouble does arise, and it will be to the advantage of all concerned if the points of difference are discussed. The main causes of disagreement are as follows:

(1) Dishonesty of the manufacturers.

(2) Open disregard of specifications by the manufacturers.

(3) Bad construction of the specifications.

(4) Conscientiousness and non-discretionary powers of the inspector.

The dishonesty of the manufacturer is a sad fact which occasionally appears in evidence, but where one instance becomes known there are a dozen that escape observation, for cheating is so easy in the majority of cases, even with careful supervision, that the temptation is hard to overcome when large financial stakes are put in hazard by absurd restrictions; but the habit once formed is too easily extended from the protection of self to the defrauding of others. It

is a physical impossibility for any one or any ten men to follow the material through the processes of manufacture to see that no false marking is done, and although it is true that the buyer has the privilege of investigating the steel at a subsequent time, every one knows that engineers do not go into the erecting shops and cut pieces out of the angles, each one of which is made to fit some one place in the structure, and then test and analyze the samples. Moreover, a dozen random tests would not show that some pieces were not wrongly marked, or that some of the metal was not entirely outside of the specifications.

It must also be considered that no ordinary tests can distinguish between Bessemer and open-hearth steel, or between acid and basic steel, while it is only the laboratory which can find whether the phosphorus is high or low. It is nevertheless a fraud for the maker to use one when the other is specified, and it is none the less a fraud on the part of the engineer toward all competitors for the contract if any change is made in the prescribed method of manufacture after making the award.

SEC. 185.—*Responsibility of inspectors.*—Inspectors should be obliged to make reports based on their own knowledge; they should know how the steel is made, and, when any fraud is suspected, should pick out the bars from which the tests are to be cut, watch these bars and see that no substitution is allowed, take drillings to unbiased and responsible chemists, and by all other means endeavor to stop the deceptions which place the honest manufacturer at a disadvantage, as well as nullify the calculations of the engineer. In so doing it is necessary to enforce the spirit rather than the letter of the law. In order to reduce the friction to a minimum, the inspector should be clothed with some discretionary power, for chemists will differ, and steel will not be absolutely uniform, and different rolled sections will give different results, but the general intention of the engineer can be carried out, and true records made of the metal which is used.

Some engineers require that inspectors shall watch every detail of manufacture by night and day. This provision may be necessary in some cases, but it is sometimes very unjust. A contract is often divided among two or more works, and it

may happen that one of these succeeds in overcoming certain difficulties by ingenuity and study. Such an advantage is the rightful property of the originator, and the works making the discovery is entitled to all the gain that may result therefrom.

Under the inquisitory system just mentioned it is impossible to keep secret any detail of manipulation, since the inspectors, who travel from one works to another, will naturally carry such information, and will volunteer any assistance in their power to unsuccessful manufacturers. This may be done from the most commendable motives and it is impossible to condemn the practice, but the result is much more pleasant to Utopian philosophers than to business rivals.

The disregard of specifications by the manufacturer often appears in substituting Bessemer metal for open-hearth, or basic steel in place of acid, or in a defiant attempt to make a steel of a different chemical composition from what is required. Assuming that the physical quality is the final criterion, a steel is furnished which passes the tensile tests, and the claim is made that, since these are filled, the material must be accepted. Astonishing, absurd, and untenable as this position is, there are cases where it has been taken and where the material has been accepted. Needless to say that by so doing the engineer places himself in an unfair relation to every works which made a bid on the better quality of material, and needless to say that such a transaction casts a deep shadow of doubt over the intention and the force of every clause in future contracts.

SEC. 186.—*Errors in engineering specifications.*—Such a concession is an open acknowledgment that the specifications were written in ignorance or error, and while it would be well if such error were recognized whenever it exists, it would also be well if carefully considered requirements were rigidly enforced. Oftentimes there are details which are plainly the result of carelessness, and these furnish an excuse for righteous wrath on the part of the manufacturer. A case of this kind occurred in filling a large contract embracing a number of foundation bolts and similar forgings. Part of these were to be made of steel running from 70000 to 80000 pounds tensile strength, while the rest were to be from 72000 to 82000. The cause of this absurdity was a change in manage-

ment during the progress of the construction with a revision of the specifications, and while the requirements for a certain portion were allowed to remain unaltered, new regulations were made for exactly similar bolts and rods for the rest of the work. In this case the reason for the divergence was evidently not in any way the result of intention, but simply an accident, and yet the inspector conscientiously refused to accept steel running 71500 pounds for one bolt, while for another, intended for exactly the same purpose, he would accept 70100 pounds. This trouble could possibly have been remedied by a short consultation with the engineer, but in this case he was three thousand miles away and was himself but a part of a complicated system of red-tape.

The possible mistakes in the specifications call for a certain amount of discretionary power on the part of the inspector, but such power is needed also to settle some small questions of detail arising in the manufacture. Thus, during the construction of a large train shed, it was found that a few angles were needed of a certain special size and section not on hand. The labor and time necessary to put in rolls to make them would have cost many times what the angles were worth, but it was necessary to make a hard fight for permission to use some angles of the same section and the same analysis and character, but which were from one-sixteenth to one-eighth inch thicker than called for. Now, it is perfectly conceivable that in a war vessel, where every pound is figured upon, a conscientious inspector would refuse to accept anything beyond the limit, and it is also conceivable that in the building of a long-span bridge the weights of all materials should be carefully watched; but that the same care is necessary, in the face of great expense and delay, in a small-span train shed, which would never have anything to do but keep the rain from the ground beneath, is one of those preposterous conceits which could only arise from misguided honesty.

A still more striking example occurred in the assembling of the angles and plates composing certain large members where it was necessary to use a few long, narrow strips not over one-sixteenth of an inch in thickness, as filling pieces between riveted work of perhaps one and one-half inches in thickness. Although this was simply a washer, and although any store-

house could supply perfectly suitable sheets of ordinary steel, the inspector required that the steel be made especially for the place, and that it should be just the same in chemical composition and physical characteristics as the angles and plates with which it was united, although this necessitated the making of special contracts with sheet mills and the delay of the erecting work.

The manufacturer does not like to bother the engineer with all these petty details arising from day to day, as it would be human nature for the busy man to answer after several such questions that contracts were made to be carried out. What the honest business man wants is a thoroughly competent inspector who knows how to make sure that he is getting what is called for; who may examine a turnbuckle with a magnifying glass, but pays less attention to an angle for a hand railing; who hammers a fire-box sheet until he knows it is right, but is a little lenient with a gusset-plate.

The proper way, in most cases, would be to place the whole matter of inspection in the hands of a competent man, who should have full authority to make such concessions or such extra tests as seem desirable during the progress of the work, in order that, on the one hand, the manufacturer is fairly treated, and, on the other, that the material is fully up to the standard required. Under any system, most of the routine work will probably be done by subordinates who are not qualified to decide all questions that may arise, but the chiefs of American inspection bureaus are fully capable of meeting all responsibility. They are specialists, who know much more about the quality and nature of steel than the constructive engineer who deals with the designing and construction of caissons and trusses. In this function of consulting expert to the bridge engineer, these inspectors will find that the conscientious manufacturer is their friend and not their enemy.

In former days the surface inspection of the material was the most important function of the inspector; to-day it is the least of his duties. In fact, it has become such a matter of form that there is a tendency toward its complete abolition. There is much to be said in favor of such a step, for it is acknowledged by all manufacturers that if an imperfection is discovered in any piece of steel, no matter if it has passed through

the hands of a dozen inspectors, the defective member must be replaced. This is done without argument, it being recognized that the maker must stand behind his goods.

Granting this condition, it will be evident that it is far better for the manufacturer to reject all unsuitable bars at the mill than to have them thrown out after delivery at distant points, and it will therefore be to his interest to properly inspect all material before shipment. For this reason it is the universal custom at rolling mills to have certain men whose sole duty it is to examine the product as fast as it is made, and separate the defective bars. This is done after the bars are straightened, and before they reach the loading beds, so that there is no further sorting to be done in the shipping yard.

The mill inspection is so carefully done in well-conducted works that it is an unusual thing for an outside inspector to reject bars, and it would be still more thoroughly performed if the manufacturer knew that the responsibility rested with him alone. In the cases where the material is to be passed upon by an outside inspector, the natural tendency is to let doubtful bars go by, since the responsibility of their acceptance is to rest upon other shoulders.

These facts are so well known that some of the best and most careful engineers in the country, including those who are most stringent in their demands concerning the chemical and physical qualities, do not make any surface inspection, but notify the manufacturer that the entire responsibility rests with him, and that a bar showing manifest flaws must be replaced, even though it has passed through every hand and has been placed in position.

Whether this practice be generally accepted or not, it is eminently desirable that the inspection bureaus should arrange to examine the material as fast as it is made, so that the delays and expense of double handling of stock may be avoided. It often happens that such handling costs more than the inspection bureau receives for its work, and it is certainly an equitable request that some action be taken to remedy this loss. The solution of this problem lies in the coöperation of the manufacturer, the inspector, and the engineer, with a realization of the fact that the interest of one is the interest of all.

APPENDIX.

Value of Certain Factors Used in Iron Metallurgy.

ATOMIC WEIGHTS.

Fe,	56	Si,	28	C,	12
Mn,	55	Ca,	40	O,	16
S,	32	Mg,	24	N,	14
P,	31	Al,	27.4	Ti,	50

CONTENT OF METALLIC IRON IN PURE COMPOUNDS OF IRON.

$FeCO_3$	$\frac{14}{29}$ or 48.28	per cent.
FeO	$\frac{7}{9}$ or 77.78	"
Fe_2O_3	$\frac{7}{10}$ or 70.00	"
Fe_3O_4	$\frac{21}{29}$ or 72.41	"

REACTIONS IN OPEN-HEARTH FURNACES.

100	pounds	$CaCO_3$	produce	56	pounds	CaO.
100	"	$MgCO_3$	"	48	"	MgO.
100	"	Si	"	214	"	SiO_2.
100	"	Mn	"	129	"	MnO.
100	"	Fe	"	129	"	FeO.
100	"	P	"	229	"	P_2O_5.
100	"	C	"	233	"	CO.
100	"	C	"	367	"	CO_2.

PROPERTIES OF AIR.

Composition by volume, O=20.9 per cent.; N=79.1 per cent.
Composition by weight, O=23.2 " N=76.8 "
Weight of 1 cubic metre, 1.293 kilogrammes.
Weight of 1 cubic foot, 0.0807 pounds.

COMPARISON OF ENGLISH AND METRIC SYSTEMS.

1 metre=39.37 inches.
1 cubic metre=35.316 cubic feet.
1 kilogramme=2.2046 pounds.
1 kilogramme per square millimetre=1422.32 pounds per square inch.
1 kilogramme per cubic metre=0.0624 pounds per cubic foot.

GRAVIMETRIC AND CALORIFIC VALUES.

NOTE.—1 Calorie will raise 1 kilogramme of water 1° Centigrade.

Factor.	Weight per cubic metre in kilos.	Calorific Value in Calories.		
		Products of combustion	Per kilo.	Per cu. metre
CO_2	1.97	. . . .	. . . .	. . . .
N	1.26	. . . .	. . . .	. . . .
CO	1.25	CO_2	2,400	3,000
H	0.09	H_2O	30,000	2,660
CH_4	0.72	CO_2 and H_2O	11,900	8,480
C_2H_4	1.25	CO_2 and H_2O	11,200	14,000
C	. . . .	CO	2,470	. . . .
C	. . . .	CO_2	8,080	. . . .
Si	. . . .	SiO_2	7,830	. . . .
P	. . . .	P_2O_5	5,760	. . . .
Fe	. . . .	FeO	1,350	. . . .
Mn	. . . .	MnO	1,720	. . . .

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